Rubberized Cord Thickness Measurement Based on Laser Triangulation – Part II: Validation

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Steel and textile cord coating is one of the key rubber processing technologies in tiremaking industry. Specifications are very demanding. In particular, thickness variation across the sheet profile and downstream is very difficult to fulfill. For in-process thickness measurement the most common are systems based on non-contact beta or gamma radiation sensors. Regardless of their wide use, non-contact radiation sensors possess serious drawbacks: they are measuring thickness in indirect way only, they are highly sensitive to variations of material properties, and probably the most critical one, they are potentially dangerous for both personnel and environment. Recent advances in optoelectronics have founded new alternative method for non-contact thickness measurement based on laser triangulation. Extremely delicate optical properties of fresh calendered rubber and severe environmental conditions create serious problems in implementation of this technology. This two-part paper presents a general conceptual framework for in-process laser-based thickness measurement, and proposes a new method for processing acquired sensory data based on statistical surface characterization. Proposed method is experimentally verified, and based on these results the new measuring systems are developed and implemented in industry.

Keywords: *Tire manufacturing, Laser triangulation, Thickness measusrement.*

1. INTRODUCTION

Calendering is one of the oldest rubber processing technologies and one of the three key mechanical processing technologies in modern tiremaking industry.

Calendering process is used for two or one side coating of the metallic or textile cord and manufacturing of rubberized cord sheet which is one of the basic semifinal products in tire manufacturing. Rubberized cord sheet is used in further tire manufacturing process as basic constructive element of tire, dedicated for accepting and transfer of load to the tire bid and finally to the rim. Thickness gradient across the calendered sheet, thickness variation along the calendered sheet (so called machine direction) as well as cord density distribution and tension determine the product quality and are closely related to the calendering process parameters. Overview of typical quality requirements of rubberized steel or textile cord sheets which are generally applied in tiremaking industry are given in Table 1 [1].

Figure 1 shows a general layout of modern calendering line for coating textile cord. The key machine in such production line is the for-roll calender in typical S configuration. First, two rubber sheets are formed in upper and lower nip (stage I of rubberized cord manufacturing). These sheets are guided further on to the middle nip, where textile cords are guided simultaneously between the rubber sheets. The cords are coated continuously by these sheets under the high pressure generated in the calender nip. Rubberized cord sheet (RCS) of the specified thickness, and width is formed at the calender output (stage II of RCS manufacturing process. The thickness of incoming sheets should be precisely controlled and maintained to specifications in order to provide necessary conditions for achieving required final RCS thickness at the calender output as well as the balance between the upper and lower rubber ply – the cords should be

Table 1: Basic requirements of rubberized steel and textile cord sheets.

Cross section geometry	
Thickness	0.4 to 2.5 mm ± 0.05 mm
Width	900 to 1450 mm ± 0.5 mm
Porosity	Not allowed
Blisters	Not allowed
Off balance	max ± 0.01mm
Weight	± 50 g/m^2
Cord specification	
Number of cords	60 to 150 cords per 100 mm
Missing cords	3 cords/100 mm for textile and 1 cord/100 mm for steel cord
Cord tension	up to 2000 daN per total width in calender area
Cord tension variation	± 250 N per total width both in calendering direction and across

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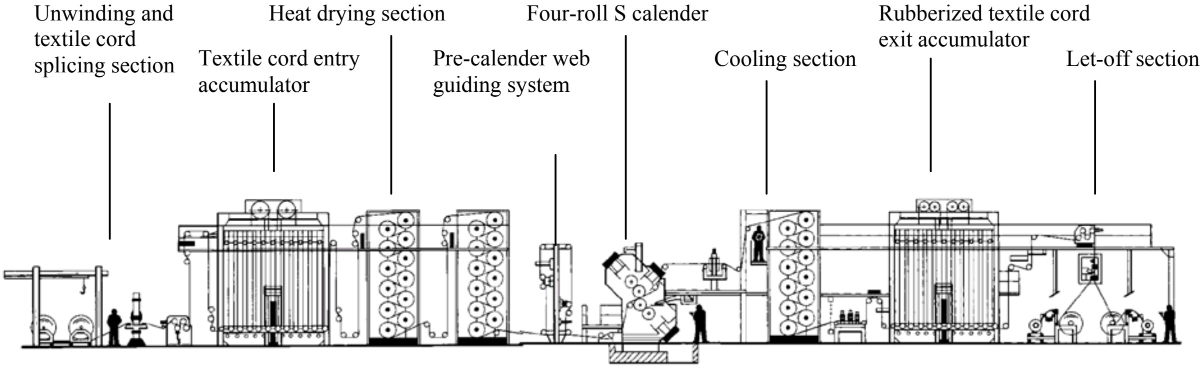

Figure 1. Typical lay-out of calendering line for coating textile cord.

precisely located in the RCS cross section, in most cases at its center. Therefore, thickness measurement of upper and lower rubber sheet as well as the overall thickness measurement of the rubberized cord at the calender output is essential for controlling the calendering process and product quality.

The thickness of the produced rubber sheets and the RCS can be controlled by changing the clearances (gaps) between calender rolls. Since all of the rolls in four-roll calender are geometrically coupled, these changes should be performed simultaneously. Extensive pressure which is generated in calender nips deflects the rolls. The deflection of each roll is not only caused by the forces arising in its own nip, but also by nip forces generated in all other calender nips because all rolls in the calender are mechanically coupled. The roll deflection generates thickness gradients across the calendered sheet, and therefore it should be compensated. Roll deflection is usually compensated by combination of roll crowning (passive compensation), by roll crossing, or alternatively by roll deflecting (dynamic and controllable compensation).

An effective rubberized cord thickness measurement and control of calendering process provides the opportunity not only for reduction of process variations and manufacturing of RCS within thickness specifications, but also for significant reductions in raw material consumption. Human operators have an inherent tendency to run calender above the target values, which means more raw material consumption than necessary. Automatic control systems can provide significant reduction of raw material by running the calender precisely to specifications. Moreover, after gaining the confidence that system is stable and can hold the average thickness of RCS precisely to specified target value without exceeding the lower tolerance limit, the target thickness can be slightly shifted down (biased) to new specification, still without exceeding the lower tolerance limit. Automatic control based on in-process thickness measurement results in more controllable manufacturing process with high accuracy and precision, which allows operator to run the system with shifted down thickness specifications and thus enables additional raw material savings. Since the nominal RCS thickness is small, from 0.4 to 2.5 mm, and modern calendering lines run at high speed, reductions in targets of few hundreds of millimeter only can accumulate remarkable quantities of raw material at annual level. For instance, in [2] is reported raw material savings up to 195.000 kg per year on a calender line that produces 36.000 square meters of RCS per day. Figure 2 depicts the key elements of this optimization strategy.

As described in [3] laser triangulation is a new enabling technology that opens the room for designing new generation of thickness measuring systems capable to efficiently replace traditional base weight heads based on radiation sensors. Specific optical conditions that normally exist at fresh calendered RCS surface as well as very hostile environment inside the calender and calender surrounding, creates a number of difficulties that hinder successful and straightforward application of laser triangulation technology. The method for effective in-process thickness estimation of RCS is proposed in [3]. In this paper are presented the results of real-world evaluation of proposed measurement method. Two examples are given. The first one is the prototype system for rubberized steel cord thickness measurement based on laser triangulation sensor with analogue photo detector, while the second one is the prototype system for rubberized textile cord scanning based on laser triangulation sensor with CCD photo detector. Both measuring systems are installed on calendering lines and extensively tested under normal industrial operating conditions.

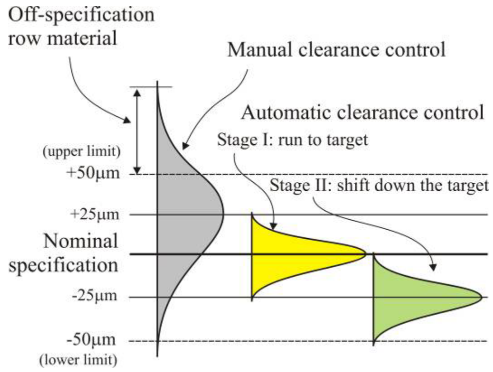

Fig. 2. Product thickness distribution achieved by manual and automatic control based on in-process thickness measurement – the concept of effective strategy for rationalization and improving economy in RCS manufacturing process.

2. MEASURING SYSTEM DESIGN

Depending of the type of calendar, various solutions of thickness measuring system are possible. Optimally configured system for four-roll calender in S configuration consists of two sets of sensors, one set for on-calender measurement and the other one for post-calender measurement (shown in Figure 3).

On-calender measurement system is dedicated for thickness measurement of rubber sheets formed in upper and lower nip. The thickness of these sheets is very important because it strongly influences the size of the rolling bank at the middle calender nip as well as the balance, i.e., the proportion between upper and lower rubber ply of produced RCS. On-calender measurement system in full configuration consists of four stationary measuring heads, two for each enter calender nips. The measuring heads should be located close to the sheet edges, typically between 100 and 200 mm. It is clear that measuring heads should be designed in such way to provide single-sided measurement, using calender roll as reference surface. Very frequently in S shaped four-roll calenders the space in the area of upper entering nip is not sufficiently large to allow installation of measuring heads. In that case, thickness measurement is performed at the lower calender nip, while thickness of the upper rubber sheet is determined analytically using the information which is provided by post-calender measurement system.

Post-calender measurement system is dedicated for thickness measurement of the finalized RCS. This measurement should be performed immediately after the middle nip as close as possible in order to reduce time delay in clearance control feedbacks. As it was already mentioned before, RCS has highly textured surface, and therefore only traverse scanning (zigzagging) is applicable, using single-sided or two-sided measuring heads in differential arrangement. In every scan equivalent thickness should be estimated for three characteristic zones (tracks) – left, center and right, based on acquired sensory data. Estimated values of equivalent thickness of the left and right track are used to control the middle nip clearances by means of cooling and drive side actuators, while estimated value of equivalent thickness of the center track is used to flatten central area of the RCS by means of cross-axis or roll bending actuators.

Besides the thickness estimation at three characteristic zones, the post-calender measuring system can be used for true profile scanning of entire RCS cross-section. This is not possible by conventional gauge heads based on radiation sensors because they have very poor space resolution, far above the sizes of the geometrical features of the RCS surface textures. Laser triangulation sensors have very small spot size, typically 50 μm, and therefore they can scan the RCS surface texture with high resolution, down to micro scales of the surface roughness level. This aspect of laser triangulation technology brings radically new possibilities. Accurate and high resolution surface scanning of entire RCS cross section texture provides additional process-related information which can be extracted from acquired sensory data. This information content can be used efficiently for more sophisticated control of calendering process that includes estimation of bank size (volume and distribution along the middle nip axial direction), rubber compound temperature and developed pressure field, cord density and cord tension, and other relevant parameters which are up to now estimated off-line only, using various mathematical models of calendering process [1, 4, 5]. Two-sided laser triangulation measurement is obvious in that case. To bring this technology into reality new scientific and engineering efforts are required.

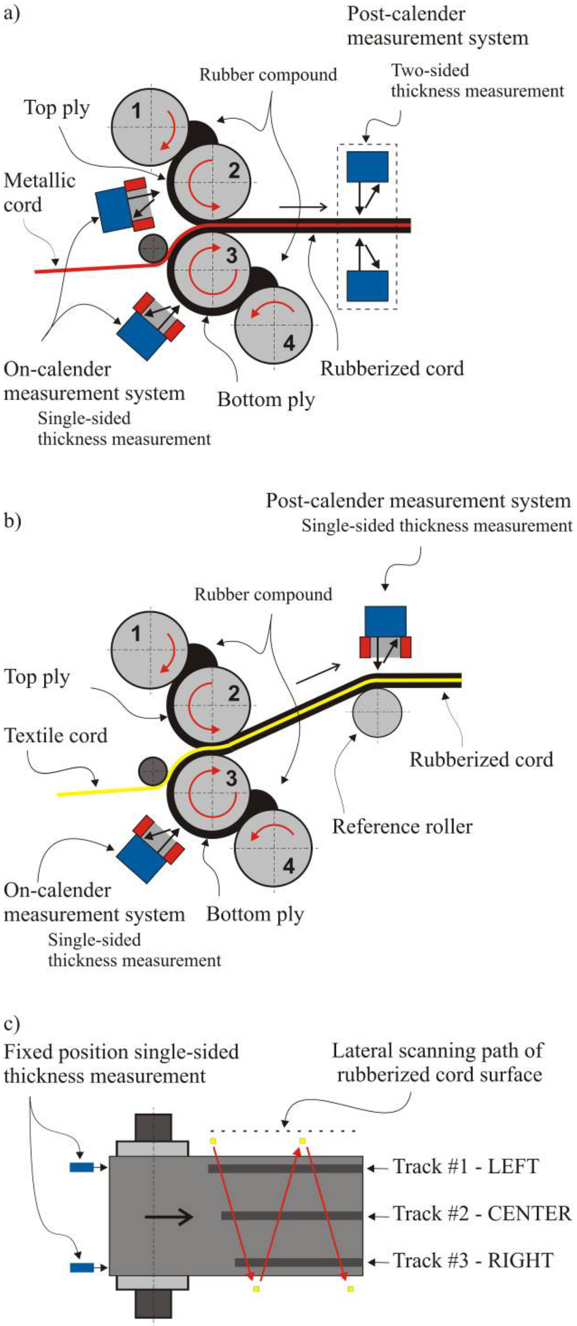

Fig. 3: Cross section of 4 roll calender in S configuration and layout of on-calendera an post-calender sensory system; (a)variant 1: full configuration, (b) variant 2: typical configuration, (c) top view of sensory layout in horizontal plane.

2.1 Single-sided measurement

The simplest method of thickness measurement is to place the RCS on a stable reference surface in which distance is known in advance, and measure the distance to the RCS top surface. The accuracy of this method is dependent on the stability of the reference surface position, as well as the properties of contact between the reference surface and the RCS itself (here it is assumed that RCS has stable contact with reference surface, otherwise this method is not applicable).

As shown in Fig. 4 absolute stand-off distance between the laser triangulation sensor and the reference surface (reference roller) SO_A is influenced by several factors generating the so called stand-off error. Elastic deformation of reference roller, internal clearance of bearings and elastic deformation of bearings generate the first partial error denoted by ε_{RD}. Geometrical runout of reference roller generates the second partial error, ε_{RR}. Imperfections of measuring head transverse guiding system generate the third partial error ε_{TG}. Therefore, the stand-off distance can be defined as a sum of nominal stand-off distance SO_0 and partial errors:

$$SO_A(t) = SO_0 + \varepsilon_{RD}(F,x,t) + \varepsilon_{RR}(x,t) + \varepsilon_{TG}(x,t) . \quad (1)$$

This means that the stand-off distance is not a simple design parameter of the measuring system that has a constant value, but the nonlinear function of time, loading conditions of reference roller (F), and lateral position of measuring head (x), which is practically impossible to predict.

Since the stand-off error is function of time its compensation based on lookup tables is not effective. In such situation only reasonable approach is providing additional sensory information which must be acquired in real-time, simultaneously with data generated by laser triangulation sensor. This approach practically leads to the differential sensor arrangement, where additional sensory system is dedicated for accurate and reliable measurement of unknown value of absolute stand-off distance $SO_A(t)$.

Probably the best candidate for that purpose is eddy-current proximity sensor, which is not sensitive to electrically nonconductive materials, such is rubber compound that is used for cord coating or rubberized textile cord as a composite material. Therefore, laser triangulation sensor and eddy-current sensor arranged as differential sensory pair can be applied for accurate single-sided measurement in on-calender measuring system using a calender work roll as a reference roll, or in post-calender measuring system but only in case of textile RCS production.

Unfortunately, when ferromagnetic material is used for reference roller, (which is typically the case) eddy current sensor may generate so called electrical runout error. This error can be suppressed, but never completely, and with lot of difficulties and computational burden. Some details related to electrical runout issue in eddy-current sensors are discussed in [7].

Besides previously discussed, there is one more disturbance which must be considered too. This disturbance is related to elastic properties of the RCS and reduction of actual thickness induces by contact force at the measuring roller. The contact force is a nonlinear function of RCS tension (F), distribution of tension force along the reference roller, the reference roller geometry (φ), and the contact angle between RCS and reference roller (ψ). Accordingly, the RCS thickness at the measuring point can be expressed as:

$$\delta = \delta_U - \varepsilon_D(F,x,\varphi,\psi) , \quad (2)$$

where δ_U denotes the thickness of undeformed RCS and ε_D is the elastic deformation function of RCC at the contact zone of the reference roller. This error is inherent to single-sided measurement method and cannot be removed.

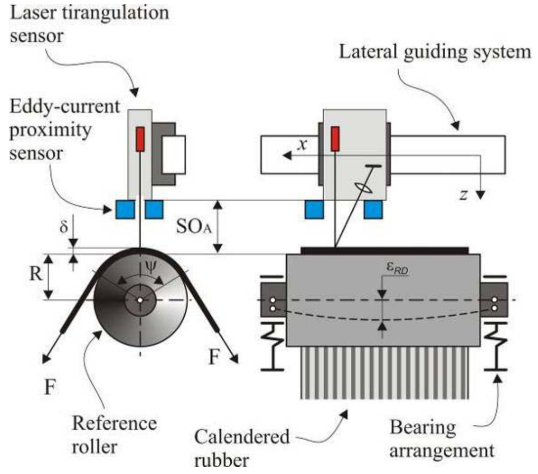

Figure 4. Sensory system configuration for single-sided thickness measurement of RCS based on laser triangulation sensor and eddy-current sensor arranged in differential configuration (variant with traversing measuring head for post-calender measurement is shown).

2.2 Two-sided measurement

In two-sided thickness measurement two laser triangulation sensors are used, arranged in differential configuration. Since the laser triangulation sensors are synchronized and their sampling rate is high, reference surface is allowed to float freely within the measuring range without affecting overall accuracy of the measuring system.

Reference roller which is used in single-sided measurement is no longer necessary. However, some kind of supporting of RCS is required in order to keep it within the measuring range of laser triangulation sensors as well as to reduce vibrations. Appropriate supporting system can be achieved by two reference rollers arranged as shown in Figure 5. Distance between the rollers should be as small as possible thus providing stable and almost vibration free guiding of the RCS in measuring zone.

From mechanical point of view, in two-sided measurement RCS is locally free of any contact force in measuring zone. As a consequence the equation (2) becomes:

$$\delta = \delta_U , \quad (3)$$

while equation (1) can be remarkably simplified by removing all error members depending of forces acting to RCS, and holding the error member which is related to uncertainties of lateral guiding system for traversing motion of laser triangulation sensors:

$$SO_D = SO_0 + \varepsilon_{TG}(x) . \tag{4}$$

The lateral guide error ε_{TG} in equation (4) is summed error for both laser triangulation sensors. In case of zero backlash, infinitely high stiffness, uniform thermal deformations and perfect parallelism of linear guides, stand-off distance will become constant, i.e., equal to nominal stand-off distance SO_0. The situation like that can be approximately achieved only in short stroke lateral traversing systems having preloaded linear guides, very stiff and rugged frame and uniform thermal dissipation field. In such case all imperfections and corresponding quasistatic errors can be easily compensated using look-up table, which can be generated periodically in appropriate time intervals by simple auto calibration procedure. However, in case that any of previously mentioned factors is not satisfied, additional sensory system should be used in order to resolve unknown lateral guiding error. In any case, perfect knowledge about stand-off distance SO_D is obvious and makes this concept of measurement almost a perfect one from technological point of view – very high accuracy and continuous scanning of both surfaces of RCS.

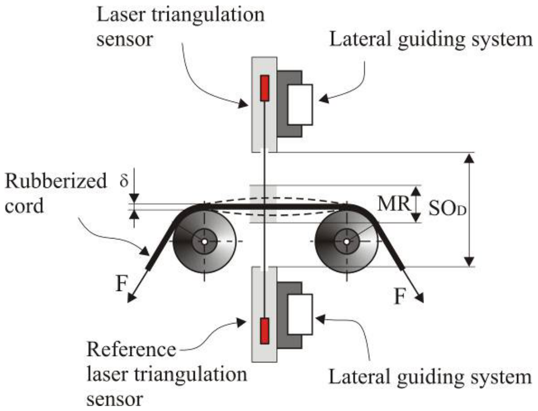

Figure 5. Sensory system configuration for two-sided thickness measurement of RCS based on laser triangulation sensors arranged in differential configuration.

3. PROTOTYPE MEASURING SYSTEM

Based on measuring method proposed in [3] and described design concept, two prototype measuring systems are developed for extensive testing in real industrial conditions.

3.1 Measuring system based on laser triangulation with analogue photo detector

This measuring system is developed for use on calendering line for production of rubberized steel cord sheets. The system is designed as two-sided scanner (very similar configuration to this one shown in Figure 5) for post-calender measurement of RCS thickness. The equivalent thickness is estimated in three zones, and this information is used for real-time control of roll nip clearances on four-roll inverted L steel cord calender.

The heart of the measuring system is laser triangulation sensor having PSD as a photo detector. The performances of this sensor are listed in Table 2.

Table 2: Basic technical performances of laser triangulation sensor used in the first prototype.

Measuring range	5 mm
Stand-off distance	205 mm
Linearity	± 5 µm (± 0.1 % FSO)
Resolution	1.3 µm (0.025 % FSO)
Mesuring rate	2 kHz
Light source Wave length Max power Laser class	Semiconductor laser 695 nm red 6mW 3B (IEC)
Spot diameter	150 x 250 µm
Temperature stability	0.01% FSO/K
Operating temperature	0 to + 45 °C

Two identical measuring modules (one of them is shown in Fig. 6), are simultaneously guided by two pretensioned linear ball bearings and driven traversal by servo controlled AC motor and a pair of mechanically coupled zero-backlash ballscrews. Lateral scanning speed is max 250 mm/sec. To insure maximum accuracy, the frame is made as heavy and rugged O-shape welded structure, carefully annealed and machined with high precision.

Lookup table is used for stand-off distance correction. Also, correction of temperature dilatation of the fame and the guiding system is applied in every scanning cycle. In that way, the geometrical stability of measuring system is obtained at the micrometer level of accuracy.

The measuring system is designed for continuous scanning of RCS thickness at high speed calenders having processing speed up to 1 m/s. The RCS effective thickness is continuously estimated in three zones (left, center and right), with user selectable width. Due to the long stand-off distance, difficult optical conditions and shadowing effect generated at inclined sides and deep valleys of highly textured RCS surface, lot of functioning problems with PSD photo detector was encountered. Although receiving imaging lens of laser triangulation sensor were very large in diameter, a small amount of reflected light, focused to photo sensitive surface of PSD was not sufficiently high to reach its lower excitation threshold. As a consequence, data dropout was frequent. Sometimes it was very high. As a quantitative measure of efficiency of used laser triangulation sensor data dropout rate was used. The data dropout rate, *ddr*, is defined as a ratio between the number of dropped data, *dd*, and the total number of laser triangulation sensor shots, *ts*, generated at predefined scanning length:

$$ddr = \frac{dd}{ts} . \tag{5}$$

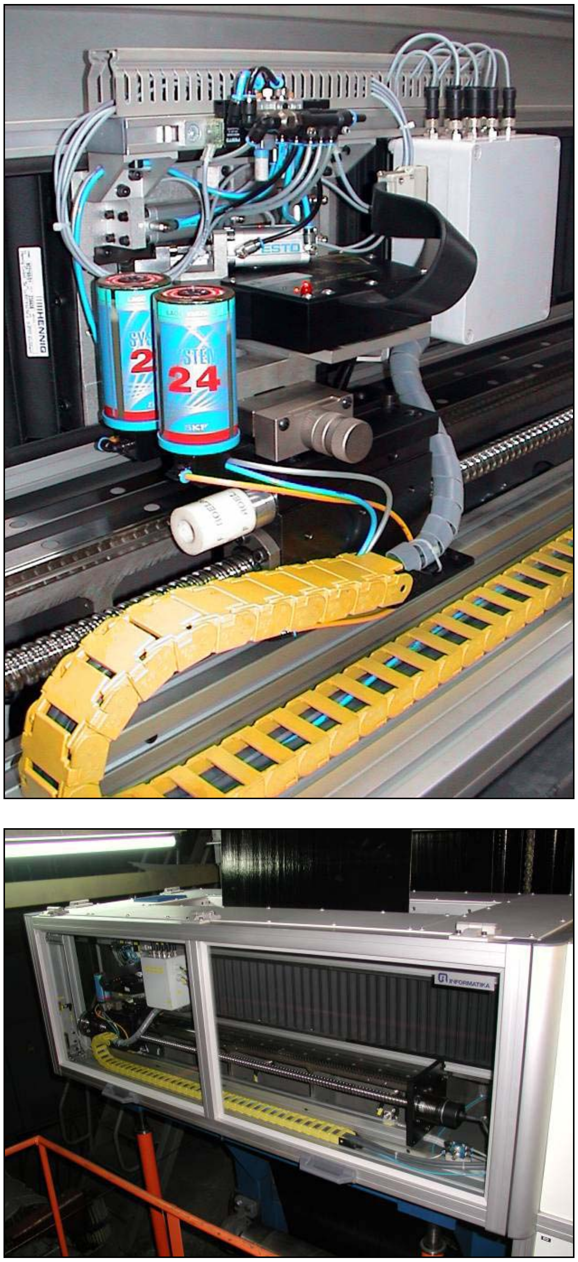

Figure 6. Prototype measuring station designed for post-calender thickness measurement of rubberized steel cord (the system was installed in Belshina tiremaking company, Belarus). Measuring module (up) and complete measuring station (down).

In two sided measurement the data dropout rate should be considered for two sensors simultaneously, since valid measurement is only this one when both sensors have valid measurements. Accordingly, the total dropout rate of sensory pair is equal or greater than the maximum one occurred at each of two sensors. Typical situation is depicted in Figure 7. For the first of two laser proximeters the dropout rate is $ddr_1 = 0.47$ nd for the second one $ddr_2 = 0.58$, while the total dropout rate of laser measuring system is high as $ddr_{SYS} = 0.79$. It means that only 21% of all measured data were valid, so the incompleteness of thickness scanned vector was extremely high.

Regardless of difficulties in used laser triangulation sensors and very high incompleteness of sensory data, estimation of effective thickness for all three zones was performed with high confidence, accuracy and stability. This was achieved by specially developed method of thickness estimation based on surface characterization. Statistical background of this method provides high insensitivity to incompleteness of sensory data.

The system is fast (2 kS/s), accurate (resolution is 1.25 μm and accuracy better than 10 μm) and environmentally absolutely safe. This system was installed in the year 2004 at Belshina tiremaking company, Belarus, and up to now operates satisfactorily. The photo of the installed system is given in Figure 6.

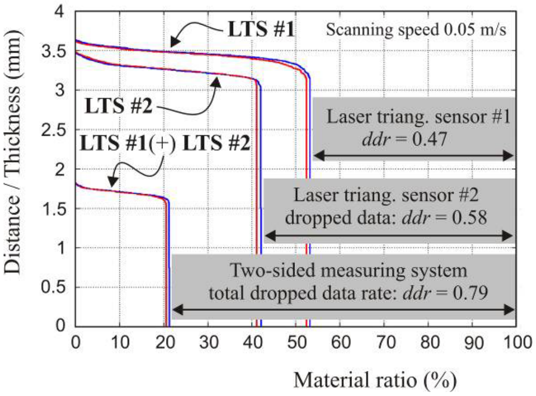

Figure 7. Partial and total dropout rates in first prototype laser measuring station used in thickness measurement of rubberized steel cord; partial and total material ratio curves are shown too.

3.2 Measuring system based on laser triangulation with digital imager

This measuring system is developed for use on calendering line for the production of rubberized textile cord sheets. The system is designed as single-sided scanner (very similar configuration to this one shown in Figure 4) for post-calender measurement of RCS thickness. The equivalent thickness is estimated in three zones, and this information is used for real-time control of roll nip clearances on three-roll inverted L textile cord calender.

In order to overcome problems observed in the first prototype, selected is laser triangulation sensor with significantly smaller stand-off distance and with highly dynamic and sensitive CCD linear array photo detector. Performances of this sensor are listed in Table 3.

Small stand-off distance requires radically different design solution of entire measuring system. Measuring module which consists of laser triangulation sensor and eddy-current sensor arranged as differential sensory pair, is very close to the RCS, and therefore exposed to very intensive heating and fumes which are normally chemically aggressive. To overcome potential problems, the measuring module is attached on the top of dedicated robotic arm having 3 degrees of freedom and thus serving as a mobile platform for carrying and positioning measuring module during scanning operation. All sensitive elements of measuring module are hermetically enclosed. In order to achieve additional protection, measuring module is overpressurized by fine filtered air which is purged through the optical path of the laser beam, removing in that way fumes that evaporate from RCS as well as the layer of hot air which can potentially generate optical errors. Temperature of measuring module is continuously monitored and in case of overheating forced cooling function based on pressurized air is activated together with other precautions depending of the current temperature level and the temperature gradient. Robotic arm which is developed at the Center for advanced technology of Mechanical Engineering Faculty of Belgrade University is shown in Figure 8.

Table 3: Basic technical performances of laser triangulation sensor used in the second prototype.

Measuring range	10 mm
Stand-off distance	30 mm
Linearity	± 3 µm (± 0.03 % FSO)
Resolution	0.5 µm (0.005 % FSO)
Mesuring rate	10 kHz
Light source Wave length Max power Laser class	Semiconductor laser 670 nm red 1mW 2 (IEC)
Spot diameter	50 µm
Temperature stability	0.01% FSO/K
Operating temperature	0 to + 50 °C

An example of single-sided scanned RCS surface and identified core profiles are shown in Figure 9. The data were acquired with 10 kHz sampling frequency and scanning speed of 50 mm/sec, which gives space resolution of 0.05 mm. Since no single data dropout was encountered, the developed system is capable to perform true scanning of visible surface of measured RCS sample.

Since RCS texture is scanned with high resolution, such collected data contain a lot of information related to the calendering process. For instance, any single cord can be accurately detected, as well as the distances between neighboring cords, which gives opportunity to count number of cords per unit length, or cords density. Cord density is one among a number of important process variables as specified in Table 1. For better visual feeling of scanned texture given in Figure 9, it is important to pay attention that horizontal and vertical axes are not in proportion (*y* axis is augmented 10 times), and therefore texture details appear to be more intensive than they are in reality. Estimated core profile limits for 10 successive tracks, each of them 10 mm in width, are shown too (lower limit is denoted by dashed line). Normally, under stable manufacturing conditions, core profile fluctuations should be small, almost negligible. In this particular sample it was not the case, which indicates that serious problems were present in calendering process. The most likely was the problem of stability of the rolling bank, which was probably at the lower limit (the case of partial/local starvation). Such situation generates unstable texture profile. This kind of instability was exactly detected in measured RCS sample.

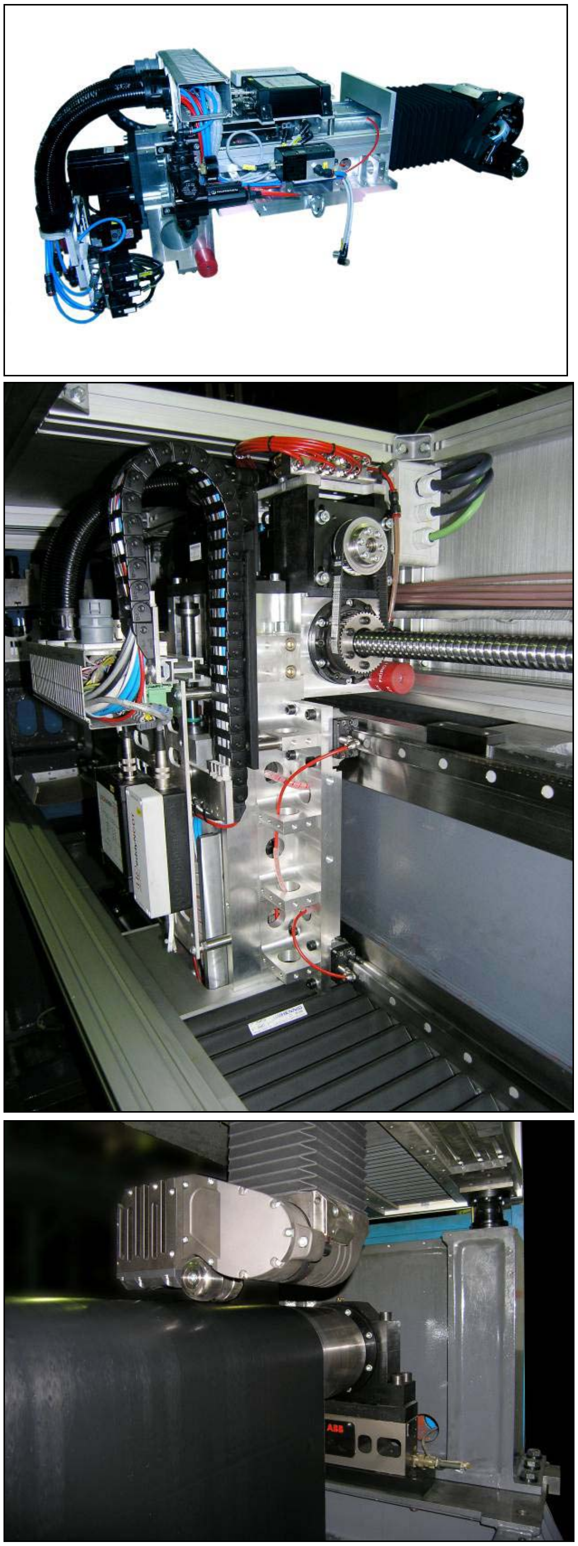

Figure 8. Prototype of measuring station designed for post-calender thickness measurement of rubberized textile cord (installed in AMTEL Voltair tiremaking company, Russia); Robotic arm module (up), traversing subassembly (center), and measuring module+reference roller with embedded RCS tension sensor and angular encoder (down).

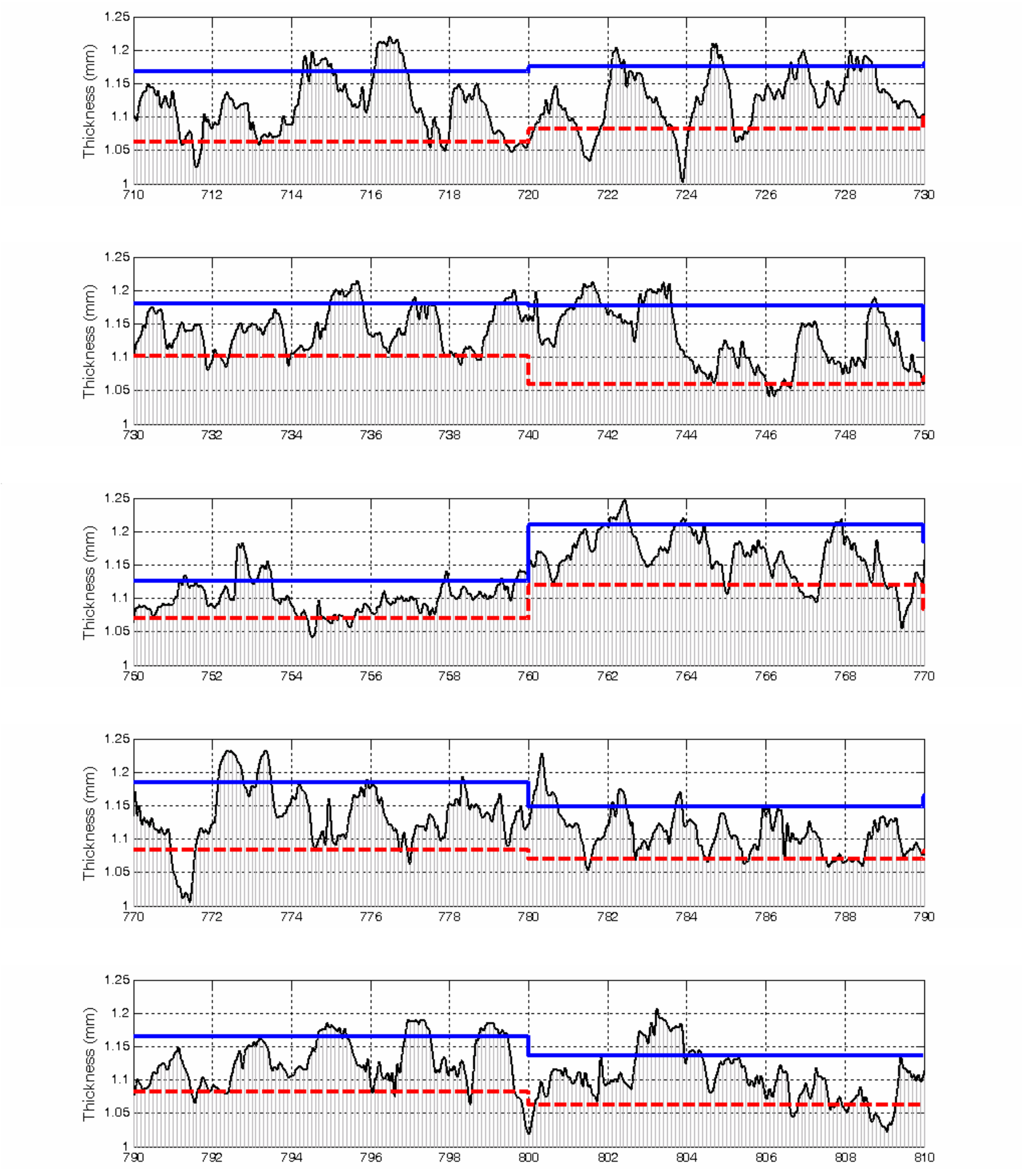

Figure 9. Example of single-sided scanned RCS surface and identified core profile measured by the second prototype; Limits of identified texture core profile are indicated by horizontal lines (dashed line for the lower limit).

Reference roller was made as rugged and geometrically almost perfect cylinder, having geometrical runout of 3.7 μm. Since reference roller is heavily exposed to thermal stresses, bearing arrangement is designed using spherical bearing at fixed side and CARB thoroidal bearing at the axially free side. Such arrangement allows accommodation of linear and angular errors in a very wide range, without parasitic internal stresses and, what is very important in this particular case, it allows reference roller to rotate almost with no vibrations. Each bearing unit is equipped with force sensor, so therefore RCS tension can be continuously monitored. Moreover, one of bearing units is equipped with angular encoder which gives ability of the system to detect length of manufactured RCS as well as speed of the calendering process.

The developed system is fast (10 kSample/s), accurate (resolution is 0.5 μm and accuracy better than 3 μm) and environmentally absolutely safe. This system was installed in the year 2007 at AMTEL Voltair tiremaking company, Volgograd, Russia. The photo of the installed system is given in Figure 8.

4. CONCLUSION

Basic configuration of sensory system for on-calender and post-calender thickness measurement at four-roll S shaped calender were analyzed and discussed in details. Two prototype systems were developed for practical evaluation of proposed laser triangulation technology, one for single-sided and the other for two-sided measurement. These systems are installed on real calendering lines. In the first prototype system which is based on long stand-off distance and PSD photo-detector, some problems was observed due to low sensitivity. As a consequence, high data dropout appeared. The problem of incompleteness of measured data was efficiently solved by surface characterization method and statistical estimation of effective thickness. The second prototype system based on CCD photo imager was very stable and practically insensitive to difficult optical properties of RCS. Almost no single data dropout was observed, and therefore this system was capable to perform true scanning of RCS surface texture. Since single-sided measurement was used in this case, only one side (optically visible) was actually scanned. Both sides scanning requires resolving of some problems related to errors generated by lateral guiding system which is used for traversing motion of laser triangulation sensors. Future research and development activities will be focused in this direction.

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МЕРЕЊЕ ДЕБЉИНЕ ГУМИРАНОГ КОРДА ПРИМЕНОМ ЛАСЕРСКЕ ТРИАНГУЛАЦИЈЕ – Део II: Валидација

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У раду су презентирана основна варијантна решења мерних станица за мерење дебљине гумираног корда применом сензора са ласерском триангулацијом. Разматране су две основне варијанте – варијанта једностраног мерња и варијанта двостраног мерења сензорским паром у диференцијалној конфигурацији. Наведена је основна конфигурација система за мерење дебљине гумираног корда на четвороваљаачним S каландрима. Резултати практичне имплементације су приказани кроз два прототипска система који су инсталирани и тестирани на реалним каландарским линијама и налазе се у редовоној експлоатацији. Ласерски систем са PSD фото детектором показао је одређене слабости, али су оне успешно компензоване развијеном методом за израчунавање ефективне дебљине применом статистичке карактеризације површи гумираног корда. Прототипски систем базиран на CCD дигиталном фотодетектору показао је одличне перформансе у реалним условима и могућност потпуног скенирања текстуре гумираног корда без изгубљених података. Ипак, недостатак овог система је у томе што се скенира само једна површина гумираног корда, чиме се губе корисне информације које се могу употребити у идентификацији стања процеса каландрирања у реалном времену. Овај проблем се може отклонити применом двостраног мерења, али је претходно неопходно разрешити одређене тешкоће, што је предмет даљих истраживања.