A New Approach to Rubberized Cord Surface Structure Identification Based on High-Resolution Laser Scanning and Multiresolution Signal Processing

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Steel and textile cord coating is one of the key rubber processing technologies in tiremaking industry. It is carried out on calendering lines where thickness variation across the sheet profile and downstream is very difficult to fulfill. Recent development of optoelectronics and derived sensory systems has enabled the replacement of traditional radioactive systems for measurement of calendered rubber thickness at calendaring lines by laser proximeters. Besides absolute work safety, laser proximeters have extreme accuracy, high sampling rate and small spatial resolution. These properties enable development of measuring systems, which besides thickness measurement enable lateral section scanning thus giving information on scanned profile roughness, overall waviness and texture. Information about profile waviness and texture can be used for identification of calendaring process parameters, which enable real-time control and optimization of this process. This paper gives a new conceptual approach for identification of surface structure calendaring process parameters based on multiresolution analysis of scanned lateral profile of rubberized cord.

Keywords: *cord rubberizing, laser, multiresolution analysis.*

1. INTRODUCTION

Rubberized cord sheet (RCS) is used in tire manufacturing process as basic constructive element of tire, dedicated for accepting and transfer of load to the tire bead and finally to the rim (Fig. 1a). Metal or textile cord within RCS carries the work load, while rubber is the feeder which gives the spatial position of cord and final geometry of tire (Fig. 1b). This structure can be considered as a kind of composite whose properties are very dependant on the quality of adhesion between rubber compound and cord. The quality of adhesion and the level of rubber compound penetration into the space between wires within cords are very important for the level of corrosion in the case of metal RCS. Sheet tension force during coating process of textile cord has tremendous effect on the level of adhesion. In the case of metal cord, steel cords are layered by special coatings, and for the purpose of contact surface increase, different kinds of strands are used. For both kinds of cord, it is very important to eliminate humidity and to keep cord wire temperature at a given level before coating process.

Cord is rubberized using rolling process which is carried out on calendaring lines. Figure 2 shows a general layout of modern calendering line for textile cord coating. The key machine in such production line is the four-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 to the middle nip, where textile cords are layered simultaneously between the rubber sheets. The cords are coated continuously by the sheets under the high pressure generated in the calender nip. Rubberized cord sheet of the specified thickness, and width is formed at the calender output (stage II of RCS manufacturing process).

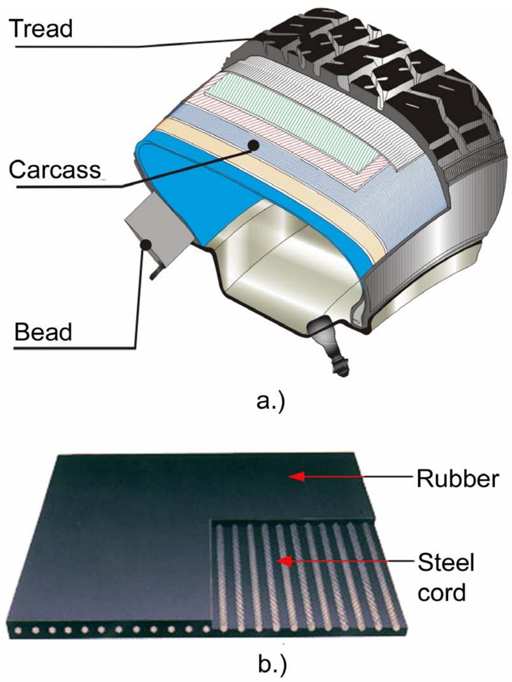

Figure 1. (a) tire cross-section and (b) rubberized cord sheet

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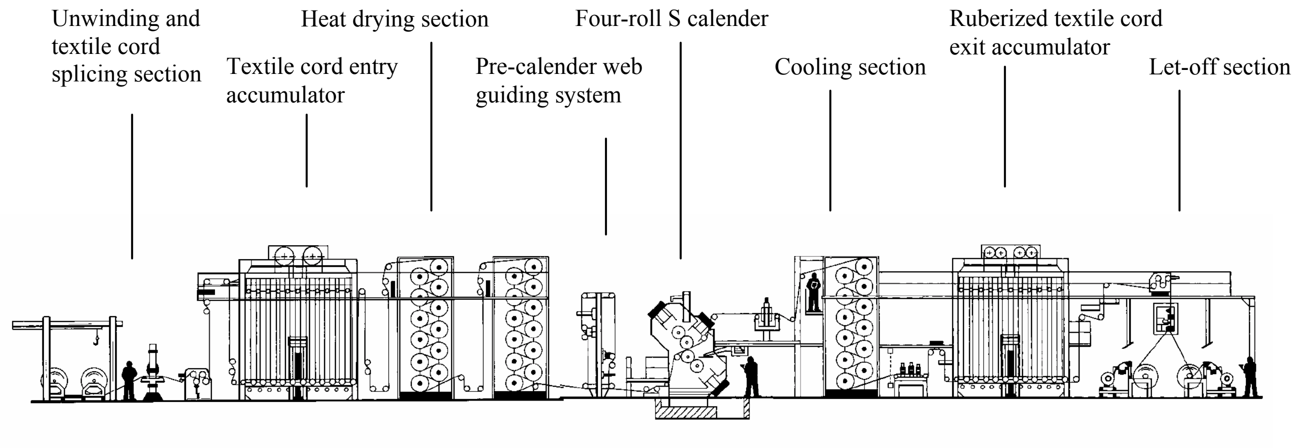

Figure 2. Typical lay-out of calendering line for textile cord

Parameters of rolling process have crucial influence on the level of adhesion between rubber compound and cord. They depend on calender power, temperature of rolls, velocity, properties of rubber compound, the level of its deformation in nips, feed uniformity and the distribution of rubber compound along nips. The tension of steel or textile sheets during calendaring is also of great importance. The thickness of incoming sheets should be precisely controlled and maintained according to specifications in order to provide necessary conditions for achieving required final RCS thickness. The cords should be precisely distributed in the RCS cross-section, in most cases in its centre. 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 calendering process control and product quality. Overview of typical quality requirements of rubberized steel or textile cord sheets which are generally applied in tiremaking industry is given in Table 1 [1].

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 ± 0.01 mm
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

As shown in Figure 3a, in ideal case, when all process parameters are well adjusted, linear RCS cross-section profile is obtained. Due to different elasticity of unvulcanized rubber and cord, the changeable friction between cord and unvulcanized rubber, as well as different temperature dilatation, the real profile is not of straight but of waved form. In this form significant waviness on micro and macro level is present (Fig. 3b). Micro waviness represents roughness of RCS and it comes as a consequence of mechanical properties of unvulcanized rubber and the effect of local surface tension in the contact with roll. Macro waviness at the texture level has regular wave shape and it comes as a consequence of impressing of cord on the top layer. Typical wavelength is 1 – 3 mm. Besides, due to nonuniform tension of RCS, profile has overall waviness.

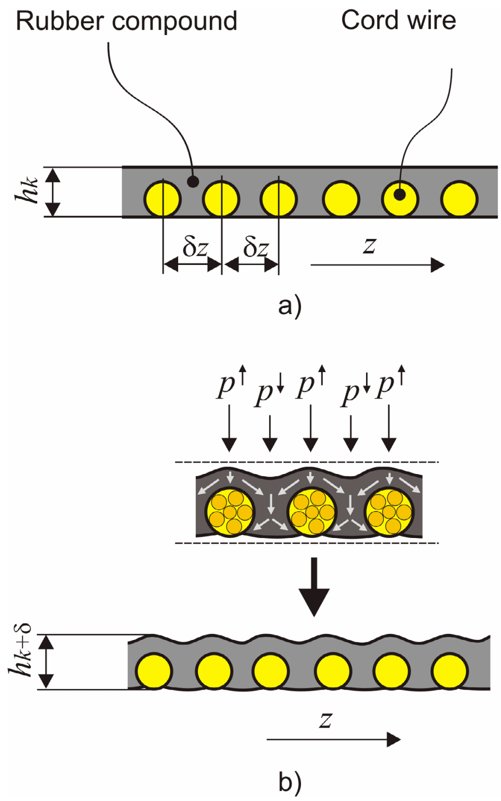

Figure 3. RCS cross-section profile: (a) ideal and (b) real

From the process parameters point of view, texture (macro waviness) is of special importance. Depending on the pressure implemented during rolling process and the rolling velocity, as well as of the amount of fed material, the level of difference between the ideal profile without texture and the real profile with texture will be smaller or greater. This difference is a complex carrier of information which can be used for identification of pressure and other parameters in rolling process. In order to make control of process parameters feasible, accurate and high resolution surface scanning of entire RCS cross-section texture is necessary. Information about each component (roughness, texture and overall waviness) of RCS cross-section profile should be isolated from sensory readings. 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 [1-3]. Control of process parameters is carried out in order to move up the real RCS cross-section profile to ideal one.

This paper gives the system for effective in-process profile scanning and identification of RCS cross-section profile based on laser triangulation methodology proposed in [4]. This paper proposes a new conceptual solution for identification of specific RCS features (roughness, texture and overall waviness) correlated to calendering process parameters. Given approach is based on wavelet transform.

2. SYSTEM FOR TWO-SIDED RCS THICKNESS MEASUREMENT

For identification of RCS cross-section profile, two-sided thickness measurement (scanning of the top and the bottom layer of RCS) at the exit from calender is needed.

In calendering process, for in-process thickness measurement systems based on non-contact beta or gamma radiation sensors are common. Regardless of their wide use, non-contact radioactive sensors possess serious drawbacks: they measure thickness in indirect way only, they are highly sensitive to variations of material properties, and they are potentially dangerous. Probably, the most serious problem with radiation sensors is their inherent risk for both, personnel and environment. These systems are also characterized by low accuracy and space resolution that give low texture scanning capabilities and make these systems unsuitable for identification RCS cross-section profile.

Laser triangulation is a new enabling technology [5] that opens the room for design of new generation of thickness measuring systems capable to efficiently replace traditional base weight heads based on radiation sensors. This technology has improved measuring properties – better accuracy, robustness and surface texture scanning capabilities (high space resolution) which give information contents sufficient not only for thickness measurement, but also for identification of RCS cross-section profile.

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. Laser triangulation sensors measure thickness directly and they collect data at much higher rates than radiation sensors do, with no needs for extensive and frequent recalibration. They have no inherent risk for personnel or environment.

For the purpose of two-sided scanning of RCS a measurement system based on laser proximeter is designed [6,7]. Laser proximity sensor for scanning applications is based on optical triangulation that serves as a basic concept for displacement measurement of diffuse target surface. Two sensors are used, arranged in differential configuration.

This is post-calender measurement system dedicated for thickness measurement of the finalized RCS. The measurement is performed immediately after the middle nip as close as possible in order to reduce time delay in clearance control feedbacks (Fig. 4). As RCS has highly textured surface only traverse scanning (zigzagging) is applicable.

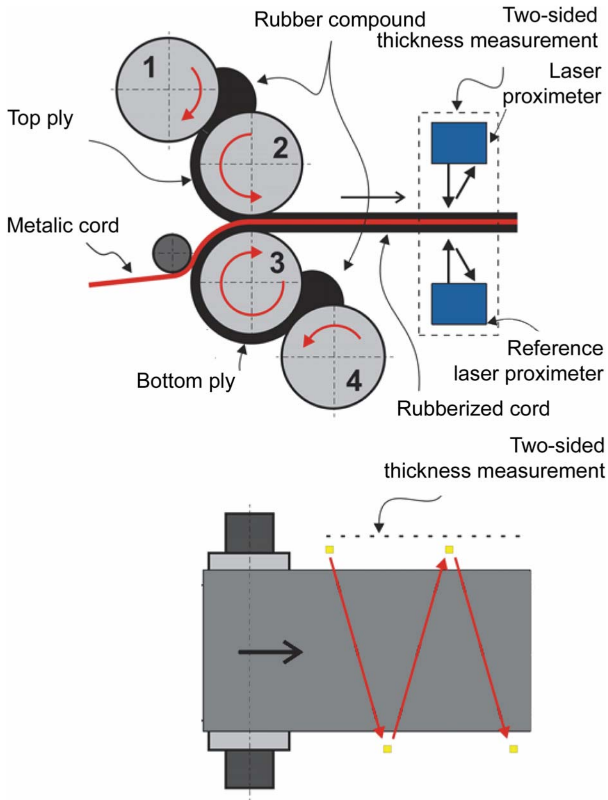

Figure 4. Cross-section of 4 roll calender in S configuration and layout of a post-calender sensory system

Prototype measuring system used in this work [7] uses laser triangulation sensor having PSD as a photo detector. The performances of this sensor are listed in Table 2.

This system was installed in 2004 at Belshina tiremaking company, Belarus, and up to now operates satisfactorily. The photo of the installed system is given in Figure 5.

Measured signal form the first measuring module carries information on the profile of the top, while signal form the second measuring module carries information on profile of the bottom layer of RCS. Figure 6 shows parts of scanned profiles of top and bottom rubber layers.

Table 2. Basic technical performances of laser triangulation sensor used

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

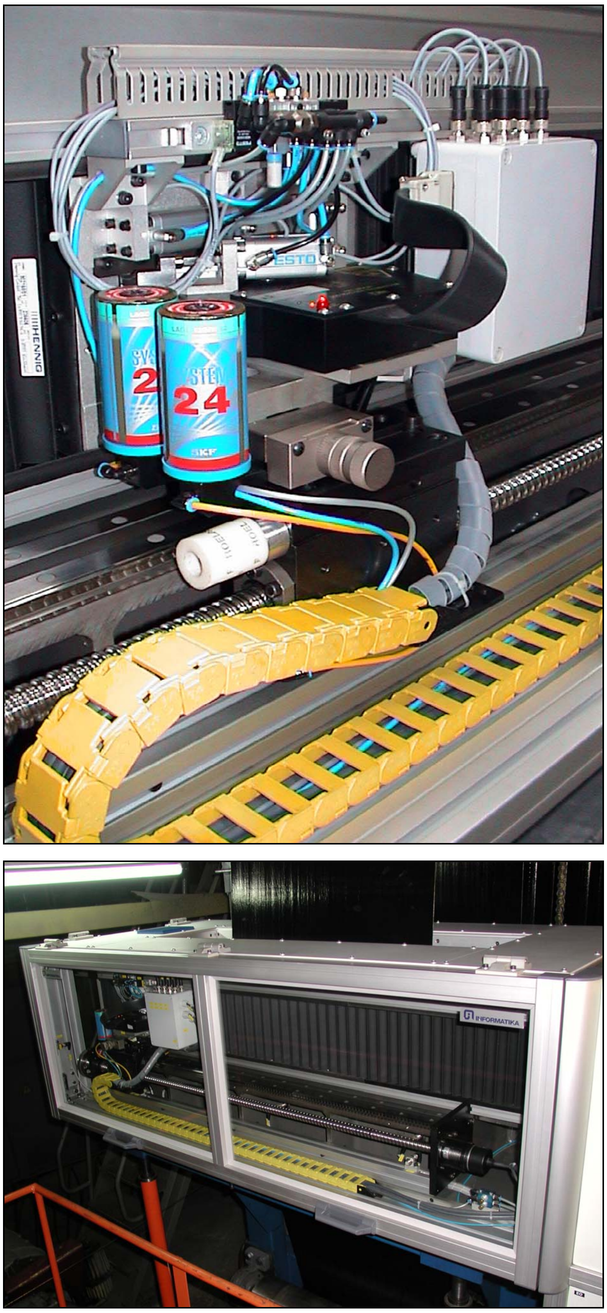

Figure 5. Prototype of measuring station designed for post-calender thickness measurement of rubberized steel cord (the system was installed in Belshina tiremaking company, Belarus); Measuring module (up) and complete measuring station (down)

3. WAVELET ANALYSIS OF SCANNED PROFILE

In order to provide control information, it is necessary to process acquired profile cross-section signals and to extract texture from overall waviness and roughness. Techniques used for this kind of analysis so far were based on filtering of signals with low pass filters.

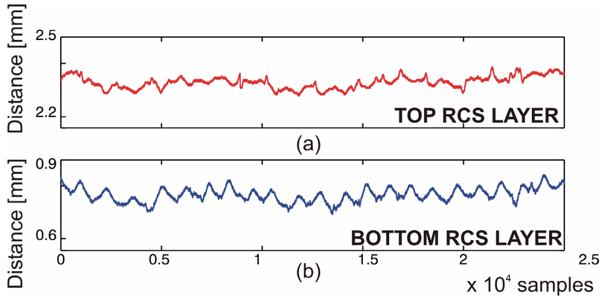

Figure 6. Parts of scanned profiles of: (a) top and (b) bottom RCS layer

Usually, one filter is used for removing roughness and texture from overall waviness, and the other one for removing roughness. Definition of appropriate filters is a very complex task, and their implementation demands a number of calculations, which is very inconvenient for real time applicability. Besides, this kind of filtering is irreversible – once filtered signal can not be reconstructed.

This paper suggests an approach for identification of texture and overall waviness of RCS profile based on wavelet transform.

3.1 Wavelet transform

Using of Discrete Wavelet Transform (DWT) signal is presented as superposition of wavelets, functions, which are obtained by translation and dilatation (in discrete steps) of single function called "mother wavelet" [8,9]. Mother wavelet and wavelets are non-periodic functions, which can be compactly supported (defined in finite time/space interval) and can be of asymmetric, irregular shapes. Thanks to these properties of wavelets, DWT is especially suitable for detection of changes in signal and their localization in time or space.

DWT can be represented as given in (1) [9]:

$$T_{m,n} = \int f(t) a_0^{-m/2} \overline{\psi(a_0^{-m/2} t - n b_0)} \mathrm{d}t \qquad (1)$$

where $f(t)$ is analyzed signal, ψ is the mother wavelet, a_0^m, $m \in \boldsymbol{Z}$ is dilatation parameter discretization (a_0 is dilation step such that $a_0 \neq 1$) and b_0 is translation step, while over-line stands for complex conjugate. Given discretization insures that narrow wavelets containing high frequency components are translated in small, while wide wavelets containing low frequencies are translated in larger time steps. Thus, DWT has better time resolution for high, and better frequency resolution for low frequencies.

Multiresolution analysis (MRA) [10] gives fast algorithms for direct and inverse DWT computation called subband filtering scheme. It aroused as a result in the field of image analysis. Its basic idea is that information a signal carries can be reorganized as a set of details, which it has on different resolutions and it can be formulated as follows. If a sequence of resolutions 2^{-j}, $j\in(0, -\infty)$ is taken, then each signal can be represented as a sum of its approximation on resolution J – $A_J f$ and details $D_j f$, $j\in[1, J]$ taken from it during passing from higher level of approximation (resolution) to the lower one:

$$f = A_J f + \sum_{j=1}^{J} D_j f \ . \tag{2}$$

Approximation at resolution 2^j, can be computed by decomposition of function f on orthonormal basis $\{\phi_{j,n}(x) = 2^{-j/2}\phi(2^{-j}x-n)$, j, $n\in\boldsymbol{Z}\}$ called scaling functions basis, where ϕ represents so called scaling function, x is variable, and n is factor which defines translation of scaling functions along x axis. Approximation of signal at resolution j is given by:

$$A_j f = \sum_n \left\langle f, \phi_{j,n} \right\rangle \phi_{j,n} = \sum_n a_n^j \phi_{j,n} \tag{3}$$

and it is characterized by a set of inner products – approximation coefficients $a_n^j = \langle f, \phi_{j,n}\rangle$, $n\in\boldsymbol{Z}$ where $\langle\ \rangle$ denotes inner product.

During approximation of a signal at lower resolution some information is lost. It is shown [9] that when certain conditions are fulfilled there is orthonormal wavelet basis $\{\psi_{j,k} = \psi(2^{-j}x-n)$, j, $n\in Z\}$, where ψ is function called wavelet, x is variable and n is factor which defines translation of wavelet along x axis, such that:

$$A_{j-1} f = A_j f + \sum_n \left\langle f, \psi_{j,n} \right\rangle \psi_{j,n} \ . \tag{4}$$

This means that details taken from a signal during passing from resolution 2^j to resolution 2^{j-1} are given by:

$$D_j f = \sum_n \left\langle f, \psi_{j,n} \right\rangle \psi_{j,n} = \sum_n d_n^j \psi_{j,n} \ . \tag{5}$$

And they are characterized by a set of inner products – detail coefficients $d_n^j = \langle f, \psi_{j,n}\rangle$, $n\in\boldsymbol{Z}$.

MRA gives fast one-pass hierarchical algorithm for computation of approximation a_n^j and detail d_n^j, coefficients, shown in Figure 7a.

Detail coefficients d_n^j are computed from approximation coefficients a_n^{j-1} by filtering it with hipass filter $\overline{G}$, and then retaining every other sample. Similarly, approximation coefficients are computed from approximation coefficients a_n^{j-1} by filtering it with lowpass filter $\overline{H}$, and then retaining every other sample. This can be formulated as follows:

$$d_k^j = \sum_n \overline{g_{n-2k}} a_n^{j-1} \ , \tag{6}$$

$$a_k^j = \sum_n \overline{h_{n-2k}} a_n^{j-1} \ . \tag{7}$$

Impulse responses of filters $\overline{H}$ and $\overline{G}$ are given by (h_{-n}), $n\in\boldsymbol{Z}$ and (g_{-n}), $n\in\boldsymbol{Z}$.

There is a reverse algorithm [10] for computation of signal f based on coefficients a_n^j and d_n^j, that is, for computation of inverse DWT. It can be described using subband filtering scheme shown in Figure 7b. Approximation coefficients are computed by inserting zero between each two coefficients a_n^j and d_n^j, then by filtering these sequences with filters H and G and finally by summing the thus obtained sequences.

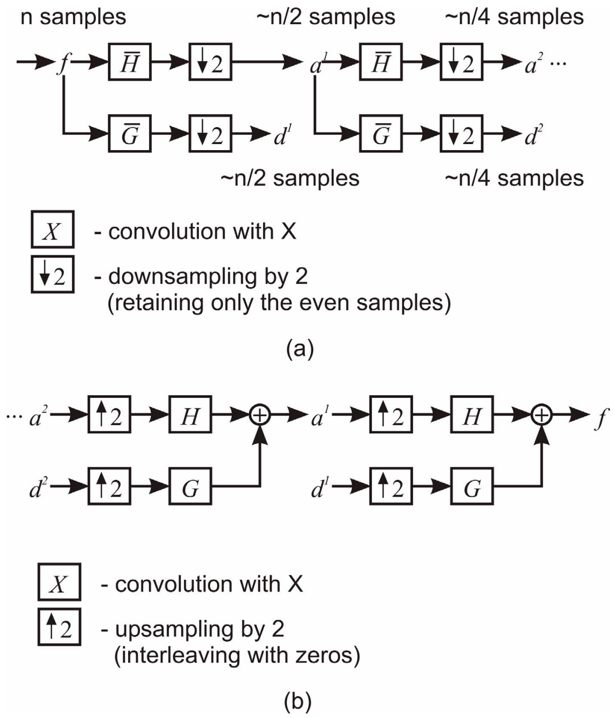

Figure 7. Subband filtering scheme for: (a) direct DWT and (b) inverse DWT

Filters H, G, $\overline{H}$ and $\overline{G}$ are conjugate mirror filters and they are computed from selected wavelets. Impulse responses of these filters are final and they can have very small number of coefficients, which is very important from the real time applicability point of view. E. g. for Daubechies wavelets this number is 2K where $K\in\boldsymbol{N}$ is the order of wavelet in a given family.

Subband filtering scheme for inverse DWT can be used for computation of approximation of signal at resolution J – $A_J f$ (eq. 4) if detail coefficients d_j^n, $j\in[1, J]$ (eqs. 2 and 5) are made zero. Details $D_j f$ can be computed similarly.

3.2 Wavelet analysis of scanned RCS profile

For analysis of RCS cross-section profiles wavelet db4 (4^{th} wavelet from Daubechies family) is chosen. The number of coefficients in impulse response of conjugate mirror filters H, G, $\overline{H}$ and $\overline{G}$ for this wavelet is 8, which means that on each level of DWT a buffer of only 8 samples is needed. This is very important when real time applicability of proposed method is considered.

Figure 8 shows some levels of approximation and details from db4 DWT decomposition of a signal given in Figure 6b. These approximations and details are reconstructed from detail and approximation coefficients calculated using subband filtering scheme shown in Figure 7.

It is obvious that approximation of a signal at level 11 contains extracted overall waviness of scanned

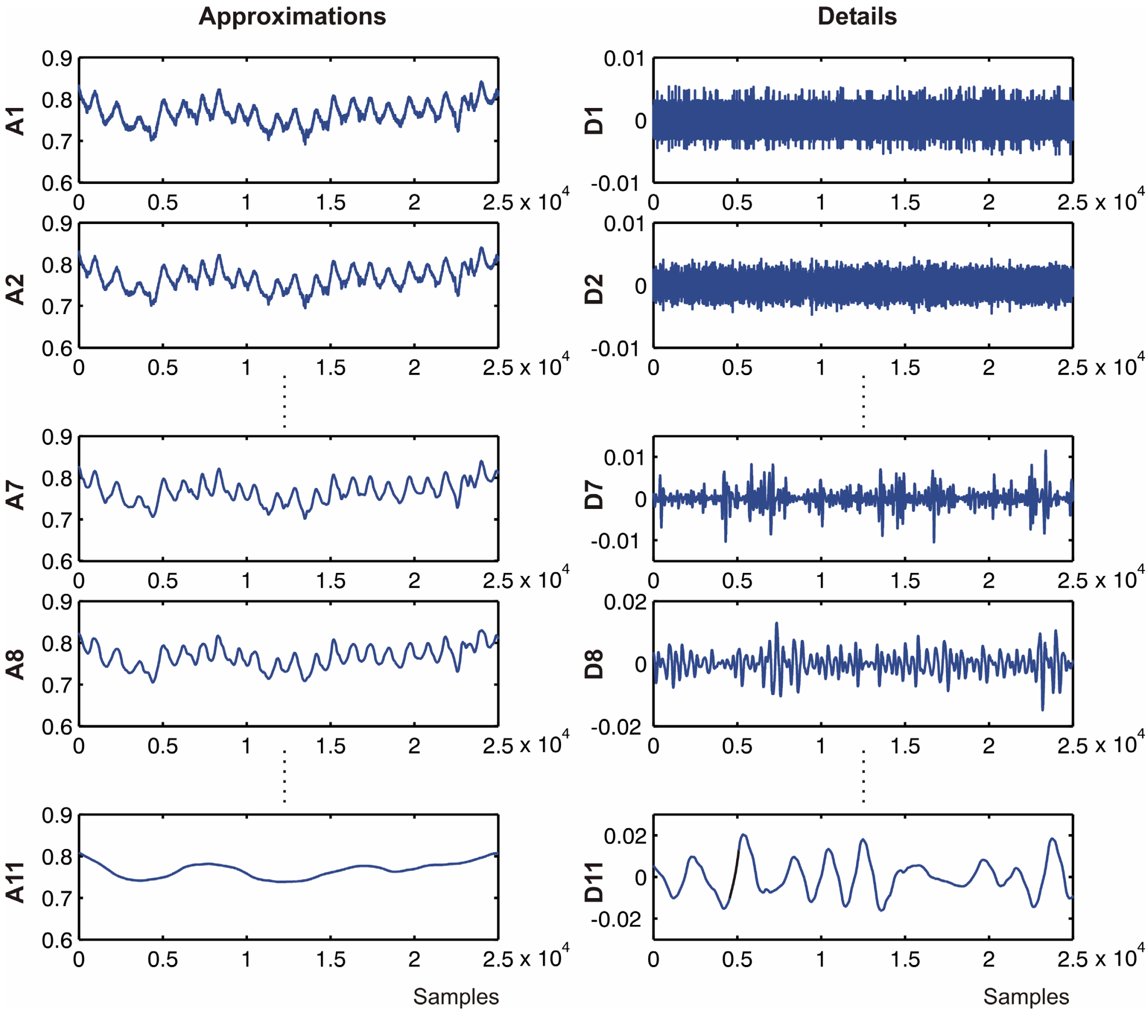

Figure 8. DWT decomposition of the signal given in Figure 6b – levels 1, 2, 7 and 11 using db4 wavelet

profile. Seventh level of transformation, on the other hand, contains texture together with overall waviness of profile. Figure 9 gives these two levels of DWT approximation in parallel with a starting signal.

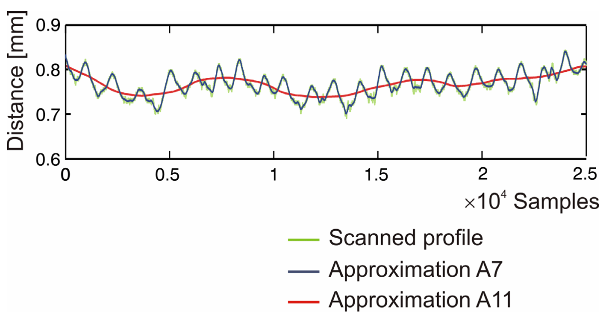

Figure 9: Comparative review of RCS bottom profile (Fig. 6b) and its DWT approximations A11 and A7

Based on given DWT decomposition, it is possible to extract information on texture from roughness and overall waviness. There are several ways to do this. From the time consumption point of view the most convenient is to declare approximation coefficients at 11th level $a_{11}{}^{n}$ zero, and to compute approximation on 7th level of thus obtained DWT. This is analogue to summing the details taken from the signal during passing from 7th to 11th level of DWT, which corresponds to subtraction of texture from the sum of texture and overall waviness. Described filtering scheme is shown in Figure 10. The texture extracted using described algorithm is shown in Figure 11. In a similar way it is possible to obtain information on roughness.

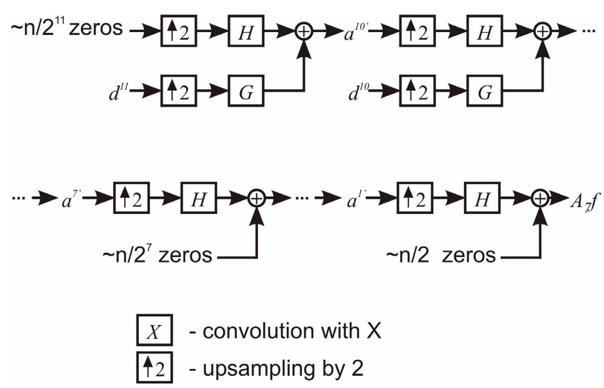

Figure 10. Filtering scheme for extraction of texture

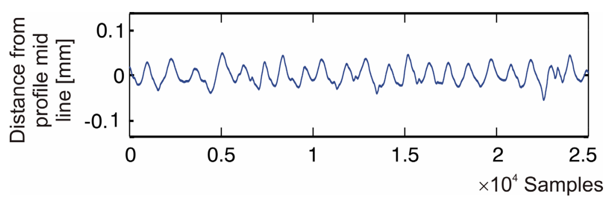

Figure 11. RCS bottom layer texture

Extracted information on texture and overall waviness can be further exploited as a basis for control of calendering process parameters. Further analysis of the texture can give information about distribution of cords within RCS, its density and tension. Besides, it can be used for estimation of rubber compound quantity – if rubber compound is insufficient it will bring to high texture. Information about overall waviness carries information on rolls deflection, as well as on tension of RCS. Further, the correlation between these information and other process parameters (such as rubber compound temperature, developed pressure field, velocity, etc.) can be established. Recognition of process parameters based on decoupled RCS cross-section profile presents a delicate research task of interdisciplinary nature and it is the subject of further research currently intensively conducted.

4. CONCLUSION

An effective rubberized cord scanning and control of calendering process provides the opportunity not only for reduction of process variations and manufacturing of RCS within 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.

Characteristic components of RCS profile are decoupled by using DWT, and component which is a basic carrier of information on rolling process is extracted. Using this information, it is possible to design control system for calendering process.

Automatic control based on in-process profile scanning results in more controllable manufacturing process with high accuracy and precision and allows operator to run the system with thickness specifications that are shifted down and enables additional raw material and energy savings. Since the nominal RCS thickness is small, from 0.4 to 2.5 mm, and modern calendering lines run at high speed, reductions of a few μm can only accumulate remarkable quantities of raw material at annual level.

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НОВИ ПРИСТУП ИДЕНТИФИКАЦИЈИ СТРУКТУРЕ ПОВРШИНЕ ГУМИРАНОГ КОРДА КОРИШЋЕЊЕМ ЛАСЕРСКОГ СКЕНИРАЊА ВИСОКЕ РЕЗОЛУЦИЈЕ И МУЛТИ-РЕЗОЛУЦИЈСКЕ АНАЛИЗЕ СИГНАЛА

Живана Јаковљевић, Петар Б. Петровић

Гумирање челичног и текстилног корда представља једну од кључних технологија процесирања гуме у производњи ауто гума. Током овог процеса који се изводи на каландрима изузетно је тешко остварити и држати константном дебљину платна. Најновији развој оптоелектронике и изведених сензорских система омогућио је да се традиционални радиоактивни системи за мерење дебљине гумираног корда на линијама за каландрирање замене ласерским проксиметрима. Поред апсолутне безбедности у раду, ласерски проксиметри поседују врхунску тачност, велику брзину узорковања и

екстремно малу просторну резолуцију. Ова својства омогућују градњу мерних станица, које поред мерења дебљине, омогућују скенирање попречног пресека обезбеђујући на тај начин информације о храпавости, текстури и свеукупној валовитости скенираног профила. Информација о валовитости и текстури може се искористити за идентификацију технолошких параметара режима процеса каландрирања, што омогућава његово управљање и оптимизацију у реалном времену.