Estimation of Fibre Orientation in Paper Products by an Image Analysis On-line System

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DOI: 10.5604/12303666.1191435

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Abstract
A paper web produced under industrial conditions always exhibits an anisotropy in its mechanical properties measured in the machine and cross directions. Proper and fast information about current paper anisotropy would significantly increase the efficiency of web quality control systems and allow to produce paper with greater precision. The main objective of the work presented was to determine the possibility of measurement of paper anisotropy. The method proposed is based on the image analysis of the orientation and location of special markers – luminescent fibres – which were introduced to the structure of the paper. Studies have shown that the method of image analysis provides a detection of fibres with a satisfactory level of efficiency, thus allowing accurate examination of the anisotropy of the paper samples analysed. On the basis of experiments, it was also found that the method of image analysis proposed allows to detect fibres with an accuracy appropriate for the problem under consideration. The invention presented has already been registered in a Patent Office as submission no. P.411294.

Key words: *paper, anisotropy, measurement, luminescent fibres, image analysis.*

Introduction

In the 21st century, the technological process of paper production is already very sophisticated and complicated. The constant tendency to increase the efficiency of the process with simultaneous optimisation of paper quality and the growing contribution of short-fibre raw materials (e.g. recycled pulps) call for better controlled methods of the process. Paper is a mass product but it still must meet the quality demands according to its end-use.

One of the most important requirements is that paper properties should be uniform throughout the area of the paper web. Unfortunately, due to process dynamics, fibres in paper structure tend to align in the machine direction (MD) rather than in the cross-machine direction (CD), which results in significant differences in paper properties in the MD and CD directions. Measurements of the effect of the Jet/Wire ratio on paper properties which were carried out under industrial conditions confirm that the greater difference between the flow-out from the nozzle of the headbox (jet) and the wire speed causes a greater difference in paper properties in the MD and CD (***Figure 1***). This difference is called anisotropy, whose magnitude can be determined by evaluation of the fibre orientation in the paper structure or by differences in mechanical and optical properties [1].

There is limited technological possibility to control and modify the anisotropy of the paper web in a paper machine. Under industrial conditions, control of this parameter can be carried out by proper modification of the jet-to-wire ratio - the proportion between the linear speed of the stock flow-out from the nozzle of the headbox and the speed of the forming wire of the paper machine [2, 11]. In order to control this property, fast and precise on-line control systems are required. Unfortunately a universal, on-line anisotropy measurement system still does not exist, therefore most of the anisotropy measurements (if any) nowadays are accomplished 'post-factum' in a laboratory. The significant dead-time between the beginning of the production of a roll of paper and the anisotropy measurement

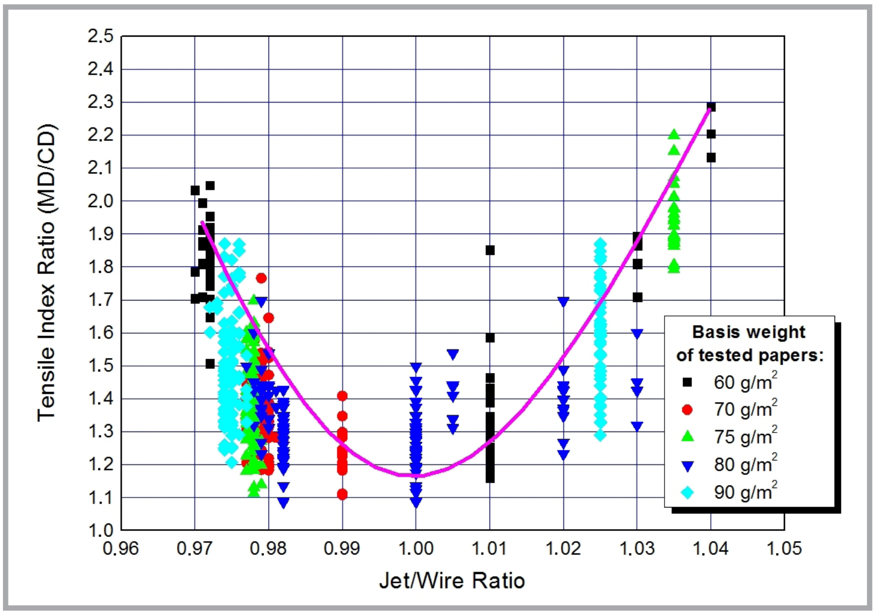

Figure 1. *Changes in the MD/CD tensile index ratio vs the jet-wire ratio for various papers produced from the same furnish and on the same paper machine (authors' results).*

after a reel change causes that it is not possible to correct any mistakes which occurred during production.

Because of the technological significance, investigations on the possibilities of on-line measuring of paper anisotropy have been carried out for several years. Drouin et al. [3] proposed a method based on light reflection from the surface of the paper web. In their method, the reflection of far IR radiation was measured in the MD and CD direction. Schaffnit [4] tried to adopt statistical methods to parametrise the variations in paper properties. The coefficient of variation of the basic weight in a certain zone in the machine direction and in the cross-machine direction were used to determine the paper anisotropy. However, both methods have not been popularised because of the insufficient accuracy.

An optical method, where laser light was used for fibre orientation measurement, was investigated by Fiadero [5]. Also ultrasonic waves were found useful for this purpose [6]. Both solutions have been applied for laboratory devices working in the off-line mode.

Tunak and Linka [7] proposed a method to measure the anisotropy of fibre systems. Their method is based on the Fourier transform. Based on the result of the Fourier transform - the amplitude spectra, graphs showing the distribution of angles of inclination of the fibres, are constructed.

The Fourier transform allows one to observe the periodicity and direction of structures in the image to determine the dominant direction. Unfortunately the method does not allow to estimate the spatial distribution of structures. Moving the same element, such as fibre, in the spatial domain is not reflected in the amplitude spectrum.

Shakespeare et al. [8] in their patent proposed an on-line method of paper anisotropy measurement based on image analysis of the paper structure. This method can be useful when the structure of the paper is distinctly visible i.e., when it is possible to distinguish individual cellulose fibres in the web. Unfortunately in several cases it is not possible. This can happen especially for recycled pulps, curled fibres, pulps with a large amount of fillers, dyes etc.

In order to eliminate the problems above, they suggested using a fluorescent agent as an additive to the pulp. In many ways it is not the optimal solution. The fluorescent agent must be properly absorbed by fibres and simultaneously should not be absorbed by other pulp components (e.g. fillers). The retention of the entire fluorescent agent is unlikely, as a result of which, part of the agent will be dispersed in the whole volume of the pulp. This might cause problems with proper recognition of the fibre orientation.

The above problems could be eliminated by using artificial luminescent fibres as markers for anisotropy measurement. To reduce the risk of inaccuracy or mistake during the measurement, the fibres should meet the following requirements: They must not affect the paper properties and must behave similar to the natural cellulose fibres in the pulp.

Our solution proposed is based on the Hough transform [13, 14], which has been successfully applied for line detection [12, 15, 16]. With its use, we can determine not only the distribution of fibre angles, but pinpoint their location and determine the length. The method has already been registered in the Polish Patent Office under the number: P.411294. A detailed description is provided in the Section ‘Image analysis’.

For the purpose of the investigations presented, artificial cellulose fibres modified with a luminescent agent were used. Since they are made of the same material as natural fibres and have similar dimensions, they should exhibit similar behaviour during the forming operation on the wire of the paper machine. In contrast to natural cellulose fibres, they can also be clearly visible under certain conditions, and thus their orientation can be easily analysed.

The main objective of the work presented was to determine the possibility of measurement of paper anisotropy by image analysis of the orientation and location of special markers – luminescent fibres – which were introduced into the structure of the paper.

Materials and data acquisition

Commercial, bleached kraft pine pulp was used in the experiments for laboratory paper production. Pulp was obtained from one of polish paper mills in form of dry sheets (dryness 93.3%). Pulp was disintegrated according to ISO 5263-1 and refined in a PFI laboratory mill to a Shopper-Riegler value of 30 °SR. Refinings were carried out according to ISO 5264-2:2002. The measurement Schopper-Riegler value was achieved according to ISO 5267-1:1999.

Cellulose pulp with a degree of polymerisation of 1250, α-cellulose content of 98% and humidity of 5% was used to obtain cellulose fibres with luminescent properties.

Cellulose spinning dope was obtained by dissolving cellulose in 50% of N-Methylmorpholine-N-Oxide (NMMO), manufactured by HUNTSMAN Holland BV. and propyl ester of gallic acid (Tenox PG) (Sigma®) was used as an antioxidant in 0.1% w/w, calculated based on the α-cellulose content. The dispersion of an inorganic modifier with luminescent properties was added directly to the mixture of cellulose and NMMO during the dissolving process. Fibres were formed with the use of the dry-wet spinning method on a laboratory-scale piston-spinning device equipped with a spinneret with 18 orifices of 0.4 mm diameter. The method of obtaining modified cellulose fibres was described elsewhere [9, 10].

The cellulose fibres containing the modifier with luminescent properties were dried and cut into the pieces of 1 ± 0.2 mm length.

***Table 1.** Technological parameters of the forming process and tensile index ratio for laboratory paper samples.*

No.	Wire drum speed, 1/min	Pump pressure for pulp flow, Pa ×10^5	Tensile index ratio (MD/CD)
1	500	1.5	1.35
2	700		1.46
3	1000		2.21
4	1200		2,29
5	1500		2.32

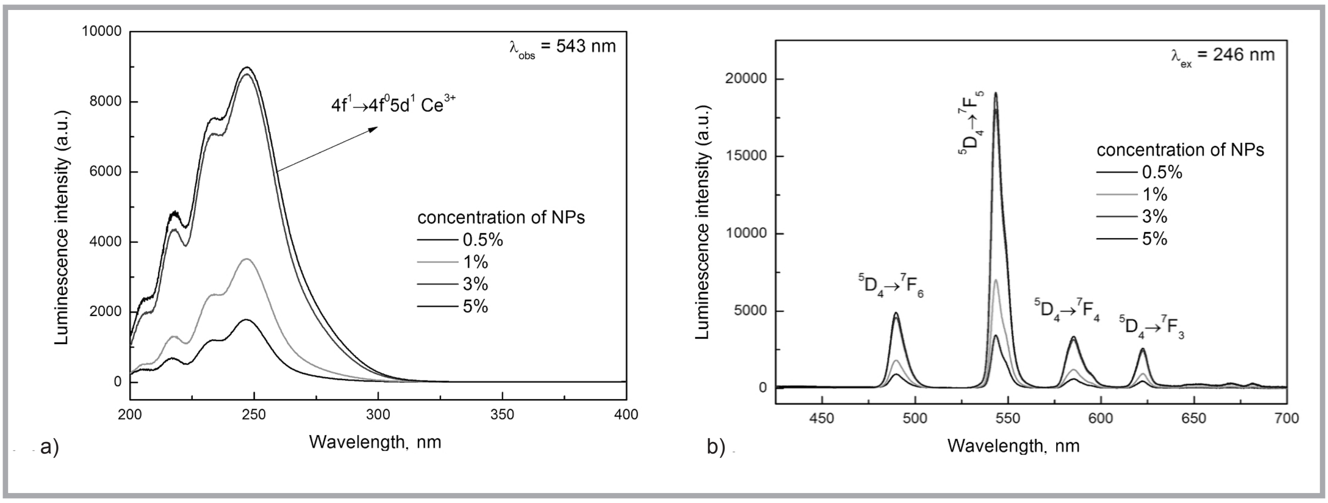

Figure 2. *Excitation a) and emission b) spectra of cellulose fibres doped with* $Ce_{0.85}Tb_{0.15}F_3$.

Figure 3. *Luminescence of prepared cellulose fibres under ultraviolet irradiation* (λ_{ex} *= 254 nm).*

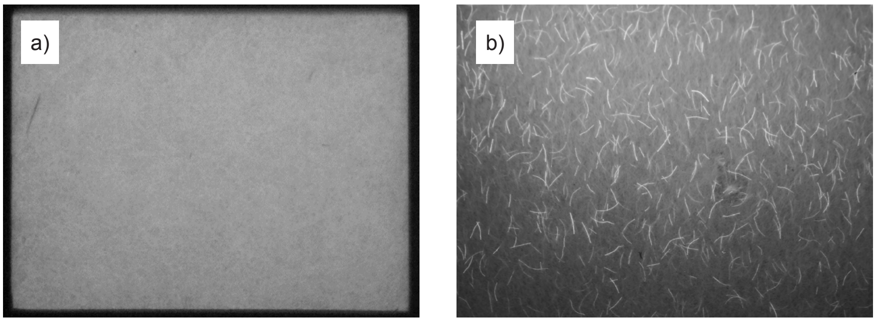

Figure 4. *Surface of paper samples observed in UV light of λ=254 nm with and without luminescent fibres; a) paper without luminescent fibres, b) paper with a content of 0.5% of luminescent fibres.*

In the present research, cellulose fibres containing 3% w/w of the modifier ($Ce_{0.85}Tb_{0.15}F_3$) were used as paper markers. For these fibres, in the excitation spectrum a wide and intensive band with a maximum at around 255 nm was present (***Figure 2***).

Figure 2 shows the emission spectra of fibres doped with the $Ce_{0.85}Tb_{0.15}F_3$ compound. The emission spectra are typical for Tb^{3+} ion. The presence of this broad band is evidence of energy transfer between Ce^{3+} and Tb^{3+} ions. The green emission of the cellulose fibres obtained (***Figure 2.B***) results from transitions between the excited electron level $^5D_4$ of Tb^{3+} ions and the ground state ^7F_J (J = 0 – 6).

The fibres obtained have relatively strong green emission (***Figure 3***), which is an important factor when the fibres are applied as a marker for the paper pulp orientation estimation process. The another advantage of the cellulose fibres with luminescent properties is their white colour, which makes them almost unnoticeable in the visible range of the light spectrum in the paper obtained. Moreover the inorganic modifier with the structure of doped fluoride is chemically and optically very stable.

Luminescent fibres in the amount of 0.5% (b.d. mass related to b.d. mass of pulp) were mixed with the refined pulp. The fibrous suspension was diluted to 0.3% and then poured into the chamber of a Formette Dynamique. Laboratory sheets of paper of variable anisotropy and a constant basis weight of 60 g/m^2 were formed. Paper forming conditions are given in ***Table 1***.

The anisotropy of the paper samples was determined using the tensile index ratio (i.e. proportion of the tensile index value measured in CD and MD). The tensile index value was measured according to ISO 1924-2:2008. A UV lamp of the SLK-UV-IR type, produced by CO-BRABiD (Warsaw, Poland), was used for determination of optical properties of the luminescent fibres.

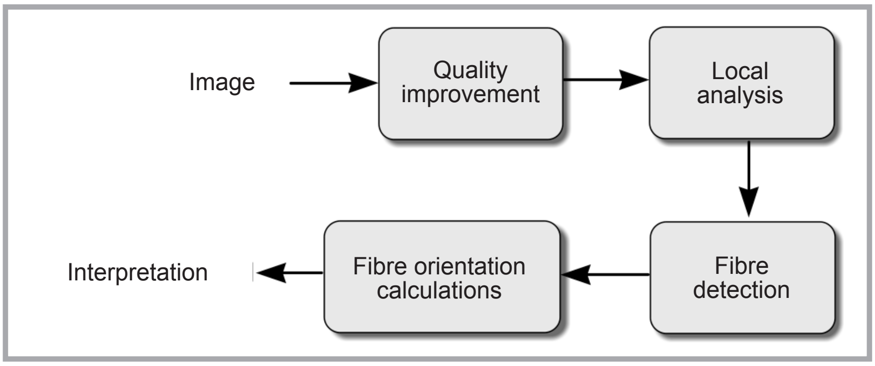

Figure 5. *Diagram of the image analysis module - which detects angles of the luminescent fibres in the paper samples.*

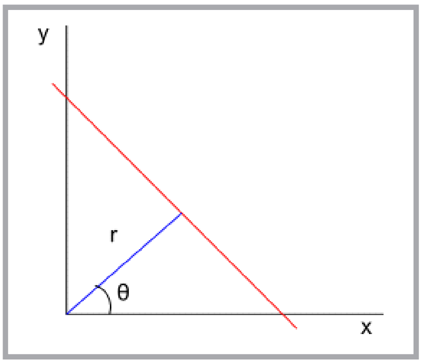

Figure 6. *Explanation of parameters.*

On the basis of images, similar to those presented in ***Figure 4***, it was proved that the markers - luminescent fibres introduced to the pulp – are clearly visible under UV light. Images were taken using a Panasonic Lumix G3 camera (exposure time: 3 sec., shutter value: 5.6).

Image analysis

The image analysis module is composed of four main blocks (***Figure 5***): the pre-processing block (phase 1) - which improves the image quality and selecting the appropriate (for further processing) colour space; the pre-processing block (phase 2) - corresponding to the local image analysis, including adaptive binarisation; the main processing unit - responsible for the detection of fibre and the post-processing block - in which coordinates of fibres are defined as follows: the beginning and the end (x_0, y_0, x_1, y_1) of fibres with luminescent properties and their inclination angles β. The exact process of image analysis is described below.

The resulting image of the paper sample, which includes the visible luminescent fibres, is fed to the image analysis module, which improves the image quality, converts the image to shades of gray and uses adaptive local binarisation to extract fibres of luminescent properties from the background. Then lines (luminescent fibres) are detected using the Hough transform (with specific parameters), which implies the representation thereof (fibre) in a polar (r, θ) coordinates system according to the relationship:

$$y=(-\frac{\cos\theta}{\sin\theta})x+(\frac{r}{\sin\theta})$$

which means: x - the x coordinate in the Cartesian coordinate system, y - the y coordinate in the Cartesian coordinate system, r - distance of straight line analysed (segment) from the beginning of the xy coordinate system (***Figure 4***), θ - angle between r and the x-axis (***Figure 6***), on the basis of which a relationship is created as follows:

$$r = x \times \cos\theta + y \times \sin\theta$$

in which r, x, y, and θ are as defined above (***Figure 6***).

Next for each non-zero (a non-background) pixel (x_i,y_i), a family of lines passing through this point is generated, the relationship of which is presented below:

$$r_\theta = x_i \times \cos\theta + y_i \times \sin\theta$$

which means: r_θ - distance of straight line analyzed (segment) from the beginning of the xy coordinate system, with an inclination θ relative to the x-axis, x_i - x coordinate of the i-th non-zero point of the image in the Cartesian coordinate system, y_i - y coordinate of the i-th non-zero point of the image in the Cartesian coordinate system

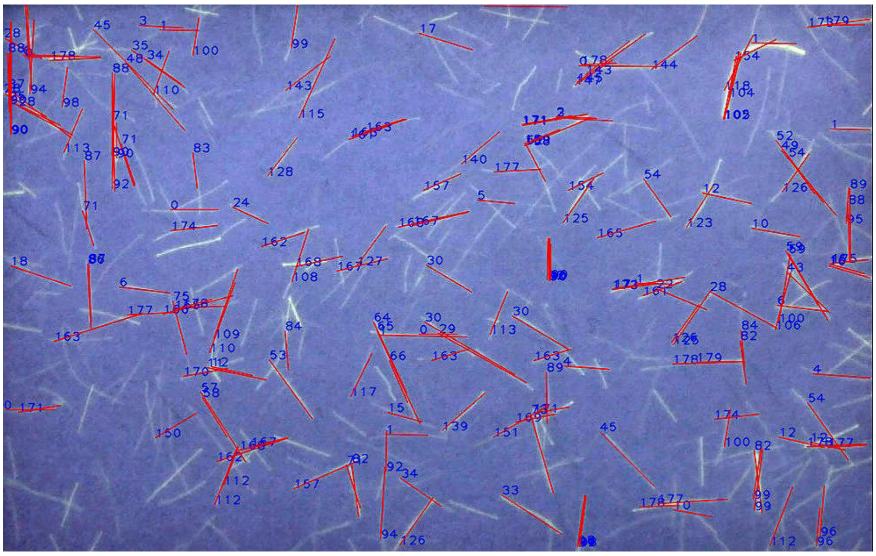

Figure 7. *Example of output of the image analysis module, with visible fibres detected, for which the the angle of deviation relative to the direction MD was calculated.*

The pair (r; θ) denotes lines (fibres) passing through point (x_i,y_i). For every point (x, y), sine waves representing the family of lines (fibres) passing through the point (x_i,y_i) are drawn. After drawing the sine waves for all points, intersections of the sine waves are indicated. Intersecting points represent points of the same line (fibre). Only the points of intersection of $y > 0$ and $0 < \theta < 2\pi$, are taken into account.

Based on the data obtained from the image analysis module, i.e. coordinates of the beginning and end (x_0, y_0, x_1, y_1) of fibres and the angles of inclination β of luminescent fibres, charts of the fibre orientation are prepared. Analysis of measurements allows to determine the anisotropy of the paper sample.

Results and discussion

In order to verify the correctness of the method of measurement proposed, experiments on samples of varying anisotropy were carried out according to the following scheme: the preparation of samples of paper of anisotropic orientation of the fibres, acquisition of an image of the paper surface with visible luminescent fibres, and analysis of the image collected. The output of these images was obtained as shown in ***Figure 7***, showing the fibres detected with marked angles of deflection. In addition, measurement data were obtained in tabular form so that their further analysis was possible.

All fibres detected were classified according to the their angle deviations with respect to the machine direction (MD). As a result, histograms of the frequency of occurrence for all fibre orientation angles (0° - 359°) were obtained. ***Figure 8*** shows examples of two paper samples which were formed under different jet-wire ratio conditions. For easier interpretation, results are presented in the form of histogram circle graphs with both directions marked (MD and CD). ***Figure 8.a*** shows results for paper formed at a comparatively equal linear speed of stock flow-out to the speed of forming wire, which results in an almost equal number of fibres oriented in the MD and CD

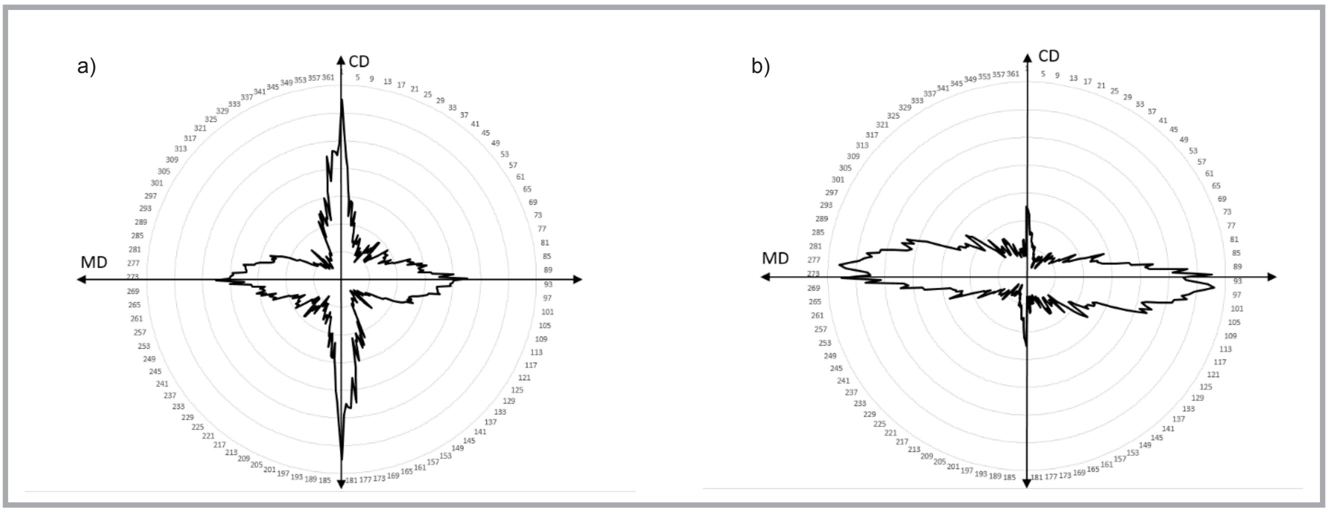

Figure 8. *Examples of fibre orientation measurements based on image analysis of luminescent fibres located in the paper web: a) wire speed of 700 r.p.m., b) wire speed of 1000 r.p.m. (pulp flow = const.).*

directions. Fibres in this paper produced with significantly different values of linear speed of stock flow-out to the speed of forming wire indicate a dominant orientation in the machine direction (***Figure 8.b***). These results were confirmed by the results presented in ***Table 1***.

The simplicity of the method presented and its independence on the furnish type causes that it can be easily adopted in industrial conditions for on-line paper anisotropy measurements. A proper control system should be located in the forming part of the paper machine. The consolidated and possibly well dewatered paper web should be locally illuminated by a proper UV source, which results in the revealing of luminescent fibres in the paper structure. Images of these fibres, captured by a camera, would be analysed and the average angular deviation from the machine direction would be calculated. The control system proposed is presented in ***Figure 9***.

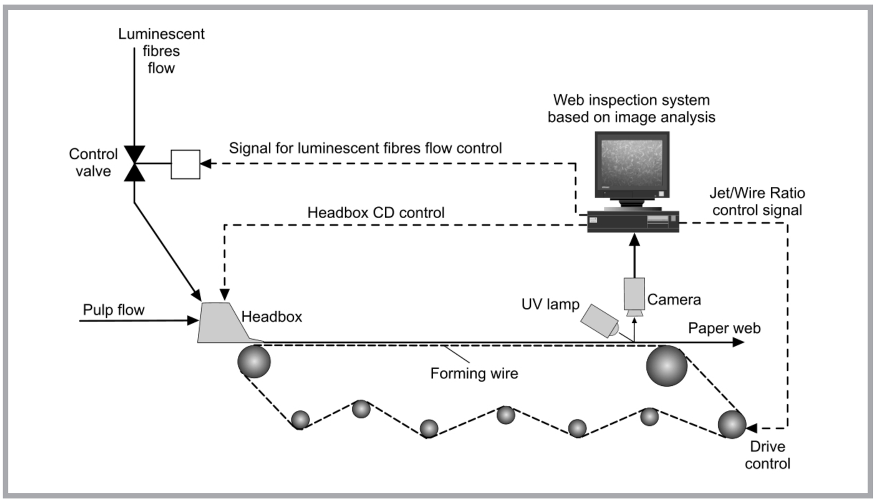

Figure 9. *On-line anisotropy measurement and headbox control system based on the method proposed.*

It was found that satisfactory results are obtained for luminescent fibres addition level of 0.5% to the furnish on the dry matter basis. It was also found that – according to the dynamics of the web forming process – the best results were obtained for luminescent fibres which contained from 0.01 to 0.2% of the luminescent compound of length smaller than 1 mm. It is worth mentioning that on-line anisotropy control could be carried out periodically (or when necessary – e.g. during grade change, paper machine speed change etc.), and luminescent fibres can be dosed only when the measurement is being conducted.

Summary

A method of anisotropy measurement of paper has been proposed, based on markers – luminescent cellulose fibres – which are added to the fibrous pulp suspension and then detected during the web forming process. Fibre orientation is determined using image analysis.

Studies have shown that the method of image analysis proposed allows detection of fibres with a satisfactory level of efficiency, thus allowing accurate examination of the anisotropy of the paper samples analysed. On the basis of experiments, it was also found that the method of image analysis proposed allows to detect fibres with an accuracy appropriate for the problem under consideration.

The method proposed can be easily applied to industrial conditions and used as an additional control system in the Quality Control System (QCS). The method presented could enable better control of the paper forming operation through the direct relationship between the jet-wire ratio and paper properties.

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Received 28.05.2015 Reviewed 01.10.2015

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