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**UNIVERSIDADES BRASILEIRAS
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REVELAM RESULTADOS PROMISSORES
À INDÚSTRIA DE CELULOSE E PAPEL**

GOOD NEWS

**BRAZILIAN UNIVERSITIES PRESENT
PROJECTS CURRENTLY BEING DEVELOPED
AND REVEAL PROMISING RESULTS FOR
THE PULP AND PAPER INDUSTRY**



ENTREVISTA — Jairo Martins, superintendente geral da FNQ, aborda os conceitos de sustentabilidade e ressalta a importância de implantá-los em todas as etapas da cadeia produtiva

INTERVIEW — Jairo Martins, General-Superintendent of the National Quality Foundation (FNQ), talks about sustainability concepts and stresses the importance of implementing them in all stages of the production chain

THE IMPORTANCE OF THE MEASUREMENT OF PAPER DIFFERENTIAL CD SHRINKAGE

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Keywords: Dimensional stability, hygroexpansibility, paper image analysis, reprographic paper, shrinkage

ABSTRACT

During the drying stage of the papermaking process, paper undergoes dimensional changes caused by fiber dehydration, but exhibiting uneven width reduction magnitudes along the cross-machine direction. The degree of cross-direction (CD) shrinkage can be very different at the edges when compared to the center of the web. The highest shrinkage amplitude at the web edges can vary according to the operation conditions and the drying section configuration as well. The difference in the degree of CD shrinkage gives rise to adverse effects on the finished CD paper sheet properties, particularly strength and hygroelastic properties, which can vary many percents from the edges to the center of the web. Extreme property values lead to different problems, such as sheet differential dimensional instability, which can limit paper quality and converting efficiency, especially in high speed machines (e.g., multi-color offset printing and office copier machines). The issues considered above make clear the advantages of measuring and carefully analyzing the differential CD shrinkage profile of finished paper. This work reviews the CD differential shrinkage profile development in the drying section, its impact on finished paper properties and presents an accurate and low cost measurement method based on image analysis techniques, supported by digital processing through the two-dimensional Fast Fourier Transform (2D-FFT). The experimental results show that image analysis applied to paper samples taken from the jumbo roll represents a reliable method for determining the differential CD shrinkage profile, and a practical tool for monitoring paper quality and evaluating its CD dimensional stability profile.

INTRODUCTION

Paper manufactured in conventional or modern paper machines invariably exhibits a non uniform cross-direction shrinkage profile across the transverse direction of the paper web, which is mostly developed during the paper drying operation. Even the most state-of-the-art highest speed paper machines tend to show the greatest differences

in shrinkage from middle to edges, although total shrinkage could be low. In the dryer section the paper web is in tension and may even be stretched in machine direction (MD) and, therefore, prevented from shrinkage in this direction. However, in the cross-machine direction (CD) the paper web is partially free to shrink even being, to a certain extent, restrained by the dryer fabrics and friction forces resulting from the contact of paper web with steam-heated dryer surfaces. In fact, the center of web is more restrained to shrinkage than the edges and this condition causes corresponding differences in CD shrinkage between those regions. The final result is the development of a non-uniform or differential transverse CD shrinkage profile.

The variation in magnitude of CD shrinkage across the paper web is of great significance for product quality and performance in end use because it affects various CD properties of the finished paper. Performance concerns are typically connected to printing operations, where strength and hygroelastics properties are of prime importance for achievement of desired high operational efficiencies, e.g., in multi-color offset printing and high speed copier machines. The higher paper edge shrinkage makes it more susceptible to defects, such as cockle, curl and grainy borders. Excessive edge shrinkage may limit the use of finished paper of the central section of the web due to quality reasons or may also cause improper conjugation of reels after rewinding operations. Here, the gain of few millimeters in web width at machine reel section may allow the production of some extra customer rolls. Both of the above situations lead to large quantity of paper being wasted and corresponding financial losses, which is clearly unsatisfactory.

The non-uniform CD shrinkage profile of paper adversely affects its quality. The differences in CD shrinkage along the transverse direction of the web lead to considerable variation in the paper CD properties at the edges, compared to the center. This is a common problem to paper manufacturers. The mechanical properties measured in cross-direction of paper may show significant percent variations along the web width. However, properties measured in machine-direction of paper exhibit small variations along the cross-direction of the web. At the edges, tensile strength and elasticity modulus are smaller than in the middle positions. In contrast, the elongation presents higher values at this location [1, 2]. The elasticity modulus in cross-direction

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of paper can be 30% lower at the edges than in the center, while in machine-direction the corresponding magnitude variation is typically around 10% [3]. A linear relationship between paper shrinkage and elongation was found in experiments carried out in early nineteen sixties [4]. Later works have shown that increased shrinkage restraint results in higher paper elasticity modulus and tensile strength, and consequently lower elongation and hygroexpansivity. The variable CD shrinkage also adversely affects the paper basis weight profile, leading to the need of increasing paper grammage at the edges of the web by accordingly decreasing the headbox slice lateral openings. However, such kind of slice adjustments creates undesired diagonal stock flows jet, which in turn disturbs fiber orientation [5, 6].

Paper hygroexpansivity, the property accountable for dimensional stability, is significantly affected by the web differential CD shrinkage. High degree of hygroexpansivity are commonly found at the paper edges, compared to the middle region of the web, and differences can reach magnitudes over 50% in reprographic paper manufactured from bleached eucalyptus chemical pulps [1, 24, 25]. In previous companion work [30], hygroexpansivity profiles development in different sections of a commercial paper machine along the manufacturing direction was analyzed. Disturbances of mentioned extent are responsible for important negative impact on the uniformity of dimensional stability along the finished paper width. In fact, at end use, paper coming from rolls corresponding to the web edges will present poorer dimensional stability than paper coming from the center area of the web. Paper dimensional instability leads to different problems in paper conversion and printing processes. Therefore, paper shrinkage minimization during manufacturing becomes of primordial importance for the dimensional stability improvement [7, 8, 9]. An essentially linear correlation between web shrinkage and paper hygroexpansivity has been determined [10], demonstrating that drying restraint increase could minimize the hygroexpansivity magnitude and, consequently, increase the paper dimensional stability. Other experiments have also demonstrated improvement in paper dimensional stability as a function of the tension applied to the paper web during drying [11]. Results indicated that an increase in web tension could reduce the paper hygroexpansivity. Further experiments of other authors have shown similar results [12, 13, 14, 23]. Other researchers have suggested the use of elongation and tensile strength measurements as indicators for indirect paper shrinkage evaluation [15, 16]. A work aimed to investigate the effect of fiber curliness, fines content, wet pressing loads and drying restraints on finished paper hygroexpansivity has revealed that hygroexpansivity is lower when paper is dried under restraint and, additionally, that refining degree, fines content and pressing loads are of small effect on the hygroexpansion index of the paper dried under restraint [14]. Studies carried out for dimensional stability analysis connected to drying shrinkage gave evidence that drying restraint could be less effective for the hygroexpansivity reduction in paper manufactured from mechanical pulps due to its smaller shrinkage potential during drying compared to grades manufactured from chemical pulps [17].

Holik [31] explains that CD profile measurement and its control have required the handling of an enormous amount of data, collecting, storing, logically combining them and displaying the results. In the present paper, it is explained the simple and effective way to analyze CD dimensional stability by the image analysis technique.

MATERIALS AND METHODS

Image analysis of paper

Image analysis techniques have been widely and increasingly applied in the pulp and paper industry research activities and process improvements. Available from mid nineteen seventies, the measurements systems supported by image analysis and processing have been used with different objectives, e.g., from dirt count to printing process quality evaluation. Equipment used for image analysis has been developed since then, moving from very expensive and complicated devices, typically used in research labs, to a variety of low cost devices presently available for image acquisition and based on two-dimensional CCD² arrays, such as electronic cameras and desktop page scanners of different types. From the middle eighties, computer processing speeds and storage capacity became suitable for the fast and outstanding improvement of the image processing technology. Currently, specific image processing programs can be loaded to any personal computer (PC). TAPPI standard TIP 0804-09 [18] provides basic guidelines concerning image analysis applied to the measurement of pulp, paper and board properties, and also to the properties of corresponding printed or coated products.

The two-dimensional Discrete Fourier Transform (2D-DFT) is a method frequently used for image analysis processing and a very convenient tool for paper CD shrinkage measurement [19]. The 2D-DFT application converts a digital image from space domain to frequency domain for identification and measurement of the periodic patterns present in paper. Considering a digital image containing M rows and N columns denoted by $f(x, y)$, with $x = 0, 1, 2, \dots, M-1$ and $y = 0, 1, 2, \dots, N-1$, the two-dimensional discrete Fourier transform of f , designated by $F(u, v)$, is given by the following expression:

$$F(u, v) = \sum_{x=0}^{M-1} \sum_{y=0}^{N-1} f(x, y) e^{-j2\pi (ux/M + vy/N)} \quad (1)$$

where $u = 0, 1, 2, \dots, M-1$ and $v = 0, 1, 2, \dots, N-1$. The exponential portion can be expanded in sinusoidal terms, whose frequencies are determined by the variables u and v (variables x and y are integrated out). The frequency domain contains the coordinates system defined by $F(u, v)$, being u and v the frequency variables. This model is analogous to the spatial domain, which results from the expansion of $f(x, y)$, being x and y the spatial variables. The spectral rectangular region defined by $u = 0, 1, 2, \dots, M-1$ and $v = 0, 1, 2, \dots, N-1$ is frequently referred as *frequency rectangle*. Clearly, the frequency rectangle has the same dimensions of the input image [20].

² CCD (Charge-Coupled Device): components used in digital cameras, scanners and other light sensor devices.

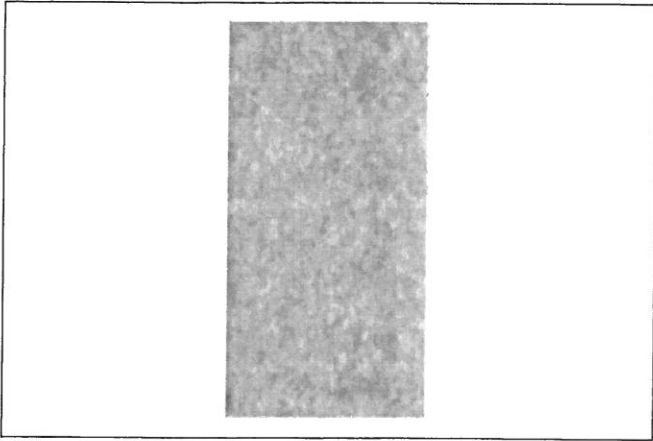


Figure 1. Digital image of a reprobographic paper sample of 75 g/m² manufactured from eucalyptus bleached kraft pulp, sized to 256 x 512 pixels (256 gray levels)

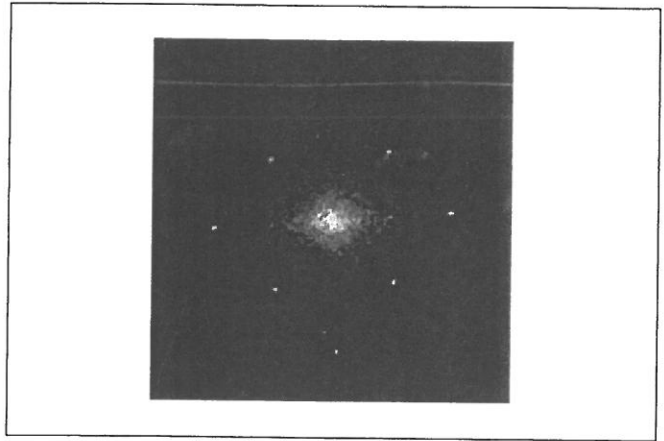


Figure 2. 2D-FFT spectrum in frequency domain obtained from the image of Figure 1 (zero-padded to 512 x 512 pixels before processing)

The Fast Fourier Transform (FFT) is based on an algorithm especially developed for computing the discrete Fourier Transform (DFT) in a faster way, but with adequate precision [21]. The 2D-FFT converts an input image in a set of sinusoidal terms, whose frequencies are limited to a finite value, but can assume any amplitude and phase values. The two-dimensional waves can be summed out in order to get the source image back (if phase angle is also known). The two-dimensional Fast Fourier Transform (2D-FFT) spectrum consists of displaying the amplitude of each frequency for proper visualization. When considered as an intensity mapping, each point in the amplitude spectrum represents a combination of a set of rows contained in the source image, where the intensity of each point reveals the source rows contrast and the relative position in the spectrum indicates the rows spacing and orientation. Figure 1 depicts the digital image of a reprobographic paper in gray scale, and Figure 2 the corresponding Fourier spectrum. The bright white dots correspond to amplitude peaks caused by a periodic pattern in the paper.

Measurement of CD differential shrinkage using image analysis

The image analysis technique used for determining the transverse CD shrinkage profile involved the detection of the forming fabric MD yarns marks left on the paper during the formation stage of the papermaking process and the measurement of the variations between them in a series of positions along the transverse direction of the paper web. Digital images were acquired from paper samples using a desktop scanner attached to a PC, where they were processed. The 2D-FFT was performed on different paper images, resulting in an amplitude spectrum in the Fourier frequency domain for each image. The samples of paper were collected from 10 subsequent and equidistant positions across the jumbo roll width by carefully cutting them in such a way that the edges were, as nearly as possible, parallel and aligned with the cross-machine direction (CD). From each sample, 5 strips were used for shrinkage measurements.

RESULTS AND DISCUSSION

Figure 1 shows an image of a 75 g/m² reprobographic paper sample collected from a 5278 mm width jumbo roll, produced on a gap former paper machine using a bleached eucalyptus chemical pulp at an operational speed of 1258 m/min. The image size was 26 mm (CD) x 52 mm (MD), consisting of a 256 x 512 pixels array, each pixel having a gray level value ranging from 0 (black) to 255 (white). The paper image was zero padded to 512 x 512 pixels before digital processing, in order to improve both the precision of measuring the wave lengths corresponding to the periodic wire marks contained in the paper and also the computational efficiency of 2D-FFT³.

Figure 2 exhibits the Fourier amplitude spectrum (frequency

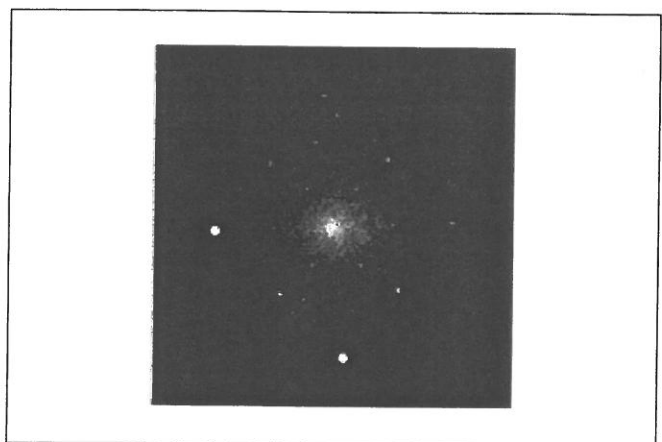


Figure 3. 2D-FFT spectrum of a paper sample image showing highlighted peaks used for CD shrinkage measurement. The peak close to horizontal axis was used for measuring the CD separation and the inclination of the MD yarns marks from machine direction. The peak close to the vertical axis was used to measure the deviation of wire CD yarns from cross-machine direction for compensation of possible misalignments of forming fabric during operation

³ Due to programming reasons, the FFT algorithms run more efficiently when source images are 2n x 2n pixels.

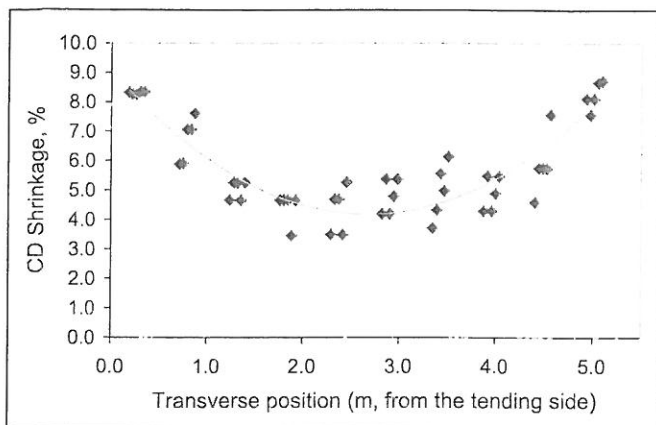


Figure 4. CD shrinkage profile obtained on samples of 75 g/m² reprographic paper manufactured from eucalyptus bleached chemical pulp by using image analysis and 2D-FFT processing

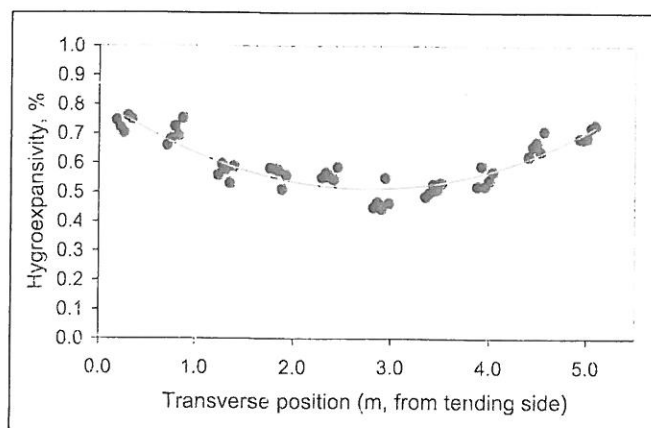


Figure 5. CD hydroexpansivity profile obtained on samples of 75 g/m² reprographic paper manufactured from eucalyptus bleached chemical pulp

domain) obtained from the source image of Figure 1 (space domain) by performing the 2D-FFT. The low areas are dark and the high areas, which include the highest amplitudes or peaks of the spectrum, such as the white dots produced by periodic marks imprinted in paper by forming fabrics, are light. Position of the peaks relative to the center of the spectrum corresponds to their particular frequencies and allows the separation between the periodic marks to be determined, since there is a well defined relationship between space and frequency domain intervals [22, 23, 24].

The same spectrum of Figure 2 is shown in Figure 3, but detaching two peaks intentionally highlighted for better visualization. Both peaks were selected from the geometrical pattern of the white dots caused by the marks of a typical SSB triple-layer forming fabric. The peak close to horizontal axis of the 2D-FFT spectrum was used for measuring the CD separation of marks produced by MD yarns of forming fabrics in paper. The angle formed by the line connecting this peak to the center of the spectrum gives a measure of the inclination of the mark lines relative to the machine-direction. The peak close to vertical axis of the 2D-FFT spectrum refers to those produced by the marks of the CD yarns. The angle formed by the vertical axis and the line connecting this peak to the center of the spectrum gives the distortion of the CD yarns relative to the cross-machine direction. The measurement of such angles allows a correction procedure to be performed in order to get the distances between marks produced by MD yarns, adjusted for eventual fabric distortion during operation.

Paper CD shrinkage was initially computed as a percentage difference of local CD separation of the forming fabric marks compared to the mean value of the series of CD separations measured in the 2D-FFT spectrum of each transverse position. The final absolute shrinkage value was then determined by combining the relative shrinkage profile with a figure of total paper shrinkage measured directly in the paper machine as the ratio of

web width at reel to that ingoing the drying section. Total paper shrinkage was found to be 5.75%.

Figure 4 shows the CD shrinkage profile determined by performing the method described above. The paper shrinkage at the edges was found as significantly higher than that in the middle areas of the web. This is a typical profile for papers dried in conventional dryer sections, comprising dryers arranged in two-tiers. The reprographic paper used in this work was dried in an hybrid dryer section consisting of single-tier dryers on the wet end section followed by conventional two-tier dryers in the last sections, particularly where the paper contraction is the most. This non-uniform CD shrinkage gives rise to uneven CD properties of paper, detachedly strength and hydroelastic properties, i.e., tensile strength, stretch, elastic modulus and tensile energy absorption [1, 25, 26]. The higher shrinkage degree at the edges also increases the sheet potential to cockle, to curl, to develop grainy edges and also to cause fiber orientation disturbances. A particular case of the impact of excessive web lateral contraction on hydroelastic properties - approached in more detail in the next paragraphs -, is demonstrated by the greater hydroexpansivity of paper in that zones, meaning that web edges will be more susceptible to dimensional instability when subjected to moisture content variations.

Figure 5 shows the paper hydroexpansivity profile, obtained by measuring this CD property on same positions considered for the CD shrinkage measurements [25]. It is noticeable that the non-uniform hydroexpansivity profile exhibits variations similar to the CD shrinkage profile, clearly confirming the influence of CD paper shrinkage on paper dimensional stability: both exhibit the same trends, i.e., lower property values at the center of the web (where drying restraint forces are more effective) and increased levels toward edges (where paper web is partially free to shrink). The highest hydroexpansivity magnitudes were found on the web edges, which correspond to the highest paper contraction areas. The furnish properties and other machine

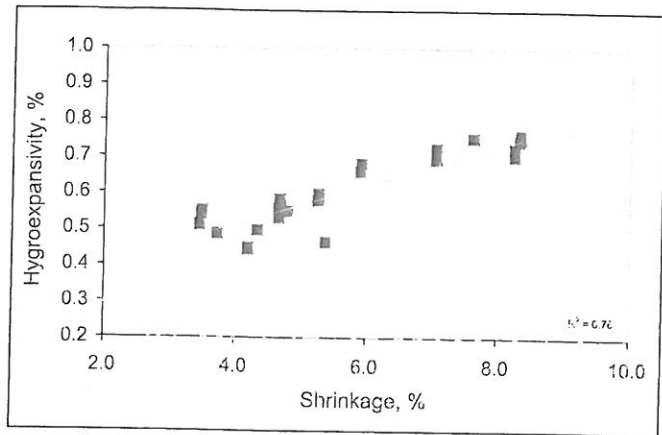


Figure 6. Correlation between CD hygroexpansivity and CD shrinkage on 75 g/m² reprographic paper made from eucalyptus bleached chemical pulp and manufactured on a commercial paper machine

conditions can also impact the differential CD shrinkage development and, consequently, the CD hygroexpansivity profile. Therefore, profiles obtained in this study are specific for the particular analyzed operational situation [28].

Figure 6 shows the correlation between the hygroexpansivity and shrinkage of paper, both measured in the cross-machine direction. The coefficient of correlation is satisfactory ($R^2 = 0.76$), demonstrating the effect of non-uniform CD shrinkage on the hygroexpansivity profile. Points located at the extreme right side of the graph correspond to the web edges, while those at the left side correspond to the center area. The trend curve slope reveals the sensibility of paper hygroexpansivity to differential CD shrinkage, meaning that adjustments in paper furnish and/or in machine operational conditions can contribute to improve this relationship, i.e., to a better paper stability at the edges of the web [29].

From the results obtained in this study, it is possible to infer that more restrained drying strategies or other machine opera-

tional settings, able to decrease paper shrinkage, would favor a better dimensional stability of finished paper.

CONCLUSION

This work gives evidence to the importance of monitoring the differential CD shrinkage of paper to meet the continuously increased demand for better paper quality and presents a practical method to evaluate paper shrinkage.

The non-uniform CD shrinkage gives rise to non-uniform CD properties of paper, particularly strength and hygroelastic properties. By measuring and analyzing the CD shrinkage across the web, papermakers can establish proper actions connected to adjustments in machine and/or process settings in order to influence lateral paper contraction and decrease its variation level, as well as improving different CD paper properties adversely affected by CD shrinkage, such as hygroexpansivity (dimensional stability).

The image analysis method presented for CD shrinkage profile measurement based on the two-dimensional Fast Fourier Transform (2D-FFT) represents a practical, useful and low cost tool for paper quality monitoring. The method approached in the present work requires simplified sampling and measuring protocols, and makes use of simple and low cost equipment. These features make it advantageous over other methods of difficult execution and questionable precision due to inherent low resolution, such as those of web marking at the wet-end based on metering fine ink drops onto the stock on the forming stage. These methods require a further tedious and laborious measurement of mark positions in finished paper. The image analysis method also offers advantages for paper dimensional stability evaluation compared to the traditional hygroexpansivity measurement method, since it is less time consuming and avoids use of more sophisticated and expensive testing equipment. ■

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