NONDESTRUCTIVE DETERMINATION OF FIBER ORIENTATION DISTRIBUTION OF PAPER SURFACE BY IMAGE ANALYSIS

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SUMMARY

Fiber orientation is a criterion used to ascertain the manufacturing district and manufacturing technique of ancient paper as a material of cultural properties. Image analysis using fast Fourier transform with suitable modifications was demonstrated to be an applicable and nondestructive method to determine the orientation angle and anisotropy. In order to improve its accuracy, two new procedures—the binarization process of the microscopic images of the paper surface and precise calculations of the average Fourier coefficients as an angular distribution by linear interpolation—have been introduced to the existing procedures. This analytical method was applied to digital optical micrographs of paper surfaces. As predicted, the method was able to distinguish among laboratory handsheet, copier paper, Japanese paper, and wood-containing paper in terms of the papermaking processes. Traditionally manufactured Korean and Japanese papers showed their own characteristic orientation behavior in accordance with the motion of the bamboo wire in papermaking.

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KEYWORDS

Fourier transform, Japanese paper, Korean paper, fiber orientation angle, anisotropy

INTRODUCTION

Pulp fibers assume a variety of spatial configurations in paper; their alignment is an important aspect of paper structures. Statistically, fiber alignment is defined as the distribution of fiber orientation as a function of angle θ when the cross-machine direction of a web or sheet is assumed to be $\theta = 0$. Fiber orientation is manifested due to the flow of pulp suspension; therefore, the flow conditions including the turbulence level and orienting shear alter it through the web or sheet thickness and across the wire plane. Fiber orientation greatly affects physical properties like anisotropy in strength, drying shrinkage and wet straining, and further curl and two-sidedness if there is a variation of in-plane orientation through the sheet thickness (Niskanen et al. 2001).

For handmade papers manufactured using traditional methods in East Asian countries, fiber orientation is very evident in spite of the manual process. This is because during dehydration, the fibers flow on a bamboo splints-aligned wire (referred to as "bamboo wire" hereafter), which is tilted in order to facilitate good formation. Even in the case of traditional European handmade papers that are manufactured mainly by the sedimentation method, the directionality, as measured by the ratio of in-plane elastic constants, was reported to be significant though the elastic constants do not always reflect fiber orientation (Waterhouse and Barrett 1991). Fiber orientation angle and anisotropy, that is, degree of orientation primarily depend on the motion of the bamboo wire (su), which is characteristic of the manufacturing district, and the manufacturing process. Therefore, fiber orientation can function as one of the criteria in the classification of ancient papers. Recently, a considerable quantity of ancient documents and historical papers have been restored using restoration paper—most of which are Japanese and Korean papers that match the properties of the original paper under restoration. In addition, fiber orientation is one of the important factors in the selection of appropriate restoration paper because it influences the shrinkage and curl of the restored paper over time.

Several methods have been developed for the estimation of fiber orientation (Niskanen and Sadowski 1989). These methods make use of anisotropy in mechanical properties such as tensile strength, elastic modulus and elastic modulus determined by ultrasound velocity, etc. The elastic modulus, which is calculated from the velocity at which ultrasound travels in paper and the apparent density of paper, is easily measured; additionally, it is a good indicator of anisotropy. However, these methods indicate only the anisotropy of the mechanical properties and do not necessarily reveal the fiber orientation distribution because they are influenced by drying restraints (Waterhouse 1994), etc. Structural properties were examined using diffraction (Yang et al. 1987, Abe et al. 1991, Fiadeiro et al. 2002) and reflection (Abe et al 1995) of light, particularly with a laser beam. More precisely, the dielectric permittivity of microwave (Osaki 1987, Habeger and Baum 1987) and X-ray diffraction can also be an appropriate parameter for anisotropy more directly related to fiber orientation, assuming that cellulose principal chains run, on an average, parallel to the fiber axis.

Some researchers employed the image analysis method for this purpose. Asplund and Norman (2004) investigated the fiber orientation anisotropy in the jet stream of nylon fibers. The fiber angle β to the machine direction was determined for each of many distinct fibers in images taken with a digital video camera under illumination of a thin sheet of laser light.

The anisotropy A was defined as $\sum_{i=1}^{n} \cos \beta_i$ divided by $\sum_{i=1}^{n} |\sin \beta_i|$. This direct method of fiber angle determination is appropriate for discrete fibers, but difficult to apply to fibers densely present in paper surfaces. More adequately for paper surface fibers, Scharcanski and Dodson (1996, 1999) used a local image gradient of all the pixels of the images by β -radiography and light transmission. They estimated orientation angle in the direction in which the total length of the projected gradient vectors is maximized. The authors developed a procedure for detecting the local facet orientation. To make the procedure more simple and quick, Sobel operators were applied as a local filtering operator to determine fiber orientation distribution in the thickness direction of paper using images of tape-split layers (Erikkila 1998), distinguish paper surface roughness (Chinga 2003) and relate the surface structure to gloss (Chinga 2004) successfully. Such local filtering operator-based procedures are excellent to accomplish a quick operation, in particular, prospectively for an on-line system. However, thick fibers are not weighted depending on their fiber width because only edges are detected sensitively by those filtering operators. Considering that there is no need for quick operation because the final purpose of determination of fiber orientation is to analyze a limited number of ancient document papers and there is need for fiber dimension-weighted orientation to predict mechanical behavior of restoration paper, the filtering operator methods were not adopted in the present work, but an alternative method of FFT analysis was adopted in spite of the time-consuming process. Yuhara et al. (1991) determined fiber mass orientation by converting the X-Y coordinates to polar coordinates to obtain a power spectrum of the mass distribution images of the paper by using soft X-ray transmission. FFT analyses were

used for video images or micrographs in textile, nonwoven (Kim Pourdeyhimi 2001, Thorr 1997), and wood fiberboard (Fujita 1995) fields. For example, Murata and Fujita (1999) introduced the technique of a circular cut and a choice of frequency range for power accumulation in order to avoid the abnormally large power in optical micrographs of fiberboard cross sections. However, the binarization process adopted here renders the circular cut unnecessary, and the unnecessary choice of the frequency range does not limit the fiber dimension to the calculation. In addition, the total power is accumulated for angles of every 11.25 degrees in his software application, which seems to be a satisfactory angle resolution for wood fiber boards, but does not for pulp fibers in paper. Therefore, the importance of a standardized and versatile system for image processing has been emphasized in this work.

The image analysis system developed here is aimed at non-contact analysis and two-sidedness detection techniques, which were originally developed for the examination of ancient documents and historical papers in combination with a digital optical microscope. Applications specific to these types of papers will be presented elsewhere, but the determination procedures were developed to be as general as possible in order to extend them to commercial paper, textile, and any type of fiber structure.

MATERIALS AND METHODS

Paper samples

The samples used were circular laboratory handsheets of 69.7 g/m^2 in basis weight prepared from beaten bleached kraft pulp, fine copier paper of 67.4 g/m^2 , handmade Japanese paper (Washi) from paper mulberry fibers of 48.9 g/m^2 , and wood-containing paper of 51.5 g/m^2 including 50 % recycled pulp.

Additionally, restoration paper designed for ancient documents and artwork was used. Two types of Korean paper (Hanji) manufactured in crafts studios in the traditional papermaking districts Uiryeong and Zangji, Korea, were used. In general, Hanji is manufactured in such a manner that an extra-fiber slurry flows out in all, particularly left and right, directions over the edges of a bamboo wire. These samples are referred to as Uiryeong-k and Zangji-k, respectively. The third sample—Yoshino-j—is a Japanese paper traditionally prepared in Yoshino, Nara, Japan with the addition of rice powder. In general, the traditional Japanese method entails that excessive on-wire slurry needs to be thrown away over the far edge of the wire from the craftsman so that residence time for fibers to agglomerate may not be given.

Values of ultrasound-determined anisotropy were calculated. The ultrasound velocity was measured every 30 degrees with a sheet sonic tester SST-110, Nomura Shoji, Japan, and the ratio of the highest velocity to its crosswise velocity was defined as the ultrasound anisotropy. The anisotropy was 1.01, 1.63, 1.87, and 2.15 for the laboratory handsheet, copier paper, Japanese paper, and wood-containing paper, respectively.

Method of acquiring surface image

A digital microscope DG-2, Scholar Co. Ltd., Japan was used to acquire reflected light images of paper surfaces with a lens of 100 times magnification. Specimens on a scanning stage were illuminated at a low angle with eight light sources arranged equidistant in a plastic cone to emphasize surface shape, as shown in **Figure 1**. Five images were captured from each of the nine evenly spaced locations; these locations were horizontally located in groups of three along the top, middle, and bottom of a sheet. The individual images were 1792×1184 pixels. The central 1024×1024 pixels region of these images corresponding to 1.66×1.66 mm² was subjected to FFT followed by the calculation of fiber orientation distribution. Micrographs taken with a scanning electron microscope (SEM), S-4000, Hitachi, Japan, were also used as

image objects for the FFT image analysis. Specimens from two separate locations within the sheet were cut into areas of 8 \times 4 mm². Micrographs were taken at a magnification of 40x using an image capture device to obtain an image size of 2392 \times 1942 pixels that is subsequently reduced to 1024 \times 1024 pixels corresponding to 1.27 \times 1.27 mm² for image analysis. Twelve SEM images of each sample were analyzed.

The restoration paper samples were photographed with the digital microscope at two locations approximately 100 mm apart within the sheet in order to examine the in-sheet variations of fiber orientation. Five micrographs were taken at each location and separately subjected to the image analysis. For these images, the bottom side corresponds to the position from which the craftsman held the wooden frame with a bamboo wire. Therefore, a fiber orientation angle of 0 degrees, for example, is equivalent to the left-and-right direction from the craftsman's view.

Conversion of Fourier transform to polar coordinates

Suppose an image f(x, y), which is composed of N^2 pixels, represents a gray level at position (x, y). In this case, Equation (1) expresses $F(k_x, k_y)$, namely, the Fourier transform of f(x, y). A power spectrum $P(k_x, k_y)$ of Fourier Transform $F(k_x, k_y)$, as defined in Equation (2), can be converted from X-Y coordinates to polar coordinates with variables *r* and θ denoting the radius and polar angle from the k_x axis, respectively.

$$F(k_{x},k_{y}) = \sum_{y=0}^{y=N-1} \sum_{x=0}^{x=N-1} f(x,y) \exp\left\{-i\frac{2\pi}{N}(k_{x}x+k_{y}y)\right\}$$
(1)

$$(k_{x}=0,1,...,N-1; \quad k_{y}=0,1,...,N-1)$$

$$P(k_{x},k_{y}) = \left|F(k_{x},k_{y})\right|^{2}$$
(2)

Fiber orientation distribution by Fourier transform

Fiber orientation can, in principle, be defined as an angular distribution of a power spectrum as a result of the integration $q(\theta)$ of a power spectrum $P(r, \theta)$ in the polar coordinates, as shown in Equation (3).

$$q(\theta) = \sum_{r=0}^{N/2} P(r,\theta)$$
(3)

The major direction of the fibers was determined by the following steps. First, a 256 gray level micrograph image was trimmed to a size of 1024×1024 pixels or 512×512 pixels (**Fig. 2a**) for fast Fourier transform (FFT). In the case of a 24-bit color image, the green component image with the maximum luminous efficiency, namely, the one to which the human eye is most sensitive, extracted from it was regarded as a gray level image for fast calculation. This is despite the fact that the general conversion from an RGB image to a gray level image requires the use of an equation that takes the red and blue components into account. However, every 24-bit color image actually looked like a gray level image with even ratios of RGB components and it was confirmed that the red or blue component images resulted in a similar orientation angle and anisotropy. Second, the images were binarized using a dynamic threshold method of a simple moving average (**Fig. 2b**). In this method, the white (level 255) or black (level 0) level of every pixel is judged by comparing it with its surrounding pixels in a 41 × 41 pixels block. The fiber width ranges from 10 to 20 pixels in the digital microscope images. The block size 41 × 41 fits this fiber size. The dynamic threshold method sets the only threshold value without any smoothing effect. Technically, an efficient routine was adopted to avoid repeated addition of the same gray levels. The

moving average method applied in this work can correct the shading of images taken under non-uniform illumination that would frequently obscure the measurement of true fiber orientation. A two-dimensional Fourier transform inevitably produces irregular large power only in the k_x and k_y axes when the gray levels of the left and right edges and the top and bottom edges of the image differ greatly because Fourier transform assumes infinite repetitions of the image in those directions. This binarization process efficiently reduces this abnormally large power by assigning an almost identical number of pixels to black or white. Additionally, this method of binarization can extract the edges of out-of-focus fibers located below in-focus top fibers even in completely out-of-focus images. The FFT was computed with these binary images using an application based on Visual Basic 6.0, Microsoft Corp. developed by the authors. **Figure 2c** is an example of a power spectrum. The FFT routine was programmed using a well established procedure (Sakai 2003).

In the process of determining fiber orientation by conversion to polar coordinates, the amplitude of the Fourier coefficient was added in a radial direction from the pole, that is, the center of the image toward the peripheral, and its mean was determined for each value of angle θ from 0 to less than 180 degrees. However, this apparently simple conversion was not as easy as we had initially expected because each discrete frequency value of the Fourier coefficients in the X-Y coordinates cannot be easily converted to the exact corresponding position in the polar coordinates. If one draws the radius of a given angle from the X-Y (practically k_x - k_y) coordinate origin, it would pass through only a few discrete positions. The interpolation was thus applied in the following manner.

Let us suppose that the amplitude of a Fourier coefficient at a position (*X*, *Y*) in the X-Y coordinates of the frequency space is A(X, Y), as shown in **Figure 3**. We calculated the amplitude A(X, Y) at angle θ and radius *r* by using linear interpolation, as shown in Equation (4). This interpolation technique is essential to the precise determination of the orientation angle and the anisotropy, as is the most unique point in the present work that have never been introduced to any methods reported previously. Next, the mean amplitude $\overline{A(\theta)}$ in every direction of angle θ was calculated according to Equation (5), and it was defined as the fiber orientation distribution in this work.

$$A(X,Y) = A(r\cos\theta, r\sin\theta) = (1-d_x)(1-d_y)A(x_n, y_n) + d_x(1-d_y)A(x_{n+1}, y_n) + (1-d_x)d_yA(x_n, y_{n+1}) + d_xd_yA(x_{n+1}, y_{n+1})$$
(4)

$$\overline{A(\theta)} = \left(\frac{N}{2} - 1\right)^{-1} \sum_{r=2}^{\frac{N}{2}} A(r\cos\theta, r\sin\theta)$$
(5)

In this equation, the addition of amplitude starts with r = 2 and not with r = 1 or r = 0. This is due to the following reason: at r = 0, A(0, 0) denotes an average of the gray level of all the pixels in the original micrograph, which does not represent directionality. Overall brightness, that is, the mean gray level of a micrograph is not related to fiber orientation; thus, A(0, 0) need not be included. Even at r = 1, A(0, 0) is partially included in the calculation except for $\theta = 0$ or 90 degrees. A(0, 0) is usually considerably larger than the other amplitudes and greatly affects the mean amplitude. In order to eliminate this adverse effect, the calculation was programmed to start with r = 2. Without this linear interpolation method, the amplitude of the Fourier coefficients with relatively large values at low frequencies would show a large error.

 $\overline{A(\theta)}$ is a function with some peaks at angle θ perpendicular to the fiber orientation direction. This curve was approximated to an ellipse. FFT followed by inverse FFT was initially performed with the curve after low-pass filtering in the frequency domain (with frequencies n > 3 cut off). This process is equivalent to an approximation to a composite

function of two sine curves with two frequencies, n = 1 and n = 2. The maximum value *a*, value *b* in the direction crosswise to *a*, and the angle α , that is, θ at $\overline{A(\theta)} = b$, were adopted as the lengths of the major axis, minor axis, and the orientation angle for elliptic parameters, respectively. **Figure 4** shows $\overline{A(\theta)}$ as a fiber orientation diagram as well as an ellipse determined by the method mentioned above from the sample image of **Figure 2**. Highly anisotropic sheets tend to be estimated to be lower than the actual anisotropy with this approximation procedure. More sophisticated approximation procedures may lead to a better fitting to an ellipse.

As for the fiber orientation parameters, the angle α represents the fiber orientation angle and the major axis *a* divided by the minor axis *b* represents the anisotropy (See **Figure 4**). Please note that, in the frequency domain, the direction of the minor axis means the fiber orientation angle because of the least ups and downs of gray levels in the major orientation direction. In order to determine the overall fiber orientation from several images for the identical sheet, the mean amplitude values of all the images were accumulated for each angle and the overall orientation angle and anisotropy were calculated in the same manner as the procedure for a single image. For determining the deviation among images of the same type of sample, a standard deviation was calculated from individual values of the orientation angle and anisotropy for every image.

RESULTS AND DISCUSSION

Figure 5, from left to right, shows images of paper surfaces photographed with the digital microscope for the four types of paper samples, their binary images, their FFT power spectra, and their fiber orientation diagrams with elliptic approximations. Each sample image in this figure was selected from more than 40 images of each paper sample to best represent its overall orientation angle and anisotropy. The fiber orientation diagrams present the overall (accumulated) amplitude values. Figure 6 shows the overall values of the fiber orientation angle and anisotropy determined from the images of the digital microscope. The error bars denote 95% confidence intervals calculated from standard deviations among images of the same sample. The laboratory handsheet was evaluated to have a certain orientation angle when a given direction was assumed to be 0 degrees; however, its 95% confidence interval was sufficiently wide to judge it as almost random. This result agrees with the very low anisotropy. For the digital microscope image, if the anisotropy is less than 1.05, the orientation is moderate or almost random; however, if it is greater than 1.10, it is clear and intense. The orientation angles of the other samples are approximately 90 degrees with a confidence interval of 1 degree or narrower. The copier paper has a relatively low anisotropy, reflecting a characteristic design that reduces wrinkle formation in the hot roll nip of copiers. Japanese paper shows the highest anisotropy. Although it is commonly believed that handmade paper does not possess fiber orientation, fiber slurry, in traditional papermaking processes, is made to flow on a bamboo wire by tilting it during dehydration. Wood-containing paper used in commercial printing also has a high anisotropy. Figure 7 shows the fiber orientation for SEM images. The orientation angle and anisotropy were consistent with those of the digital microscope images in spite of wider confidence intervals; this was because a fewer number (twelve) of images were subjected to calculation. The anisotropy level is lower on the whole for the SEM images than for the digital microscope images. Fibers are not extracted properly in the binary SEM images as the fibers body appears mottled in black and white dots except their clearly white edges. In contrast, the whole fibers appear white in binary digital microscope images although their edges appear rather indistinct. The mottled appearance of the fibers in the SEM images is considered to lower the anisotropy. Anyway, the result demonstrated that the image analysis using FFT functions properly in order to compare papers relatively although the anisotropy level is influenced by the image acquisition method. Figure 8 shows the

comparison in anisotropy between the FFT analysis applied to the two types of paper surface images and the ultrasound method. There is an anisotropy inversion between the Japanese paper and the wood-containing paper. Ultrasound anisotropy does not represent the two-sidedness because of its wavelength is usually shorter than paper thickness. Therefore, ultrasound anisotropy reflects the elastic modulus over the whole thickness of the sheet. Japanese paper is often manufactured with the bamboo wire shaken in the left-and-right direction from the craftsman's view as well as back-and-forth direction. The left-and-right shaking is conducted in the middle of the sheet forming process, thus generating the left-and-right orientation in the inner layer of the sheet despite the dominant back-and-forth orientation in the outer layers. This is the reason why, for the Japanese paper, the ultrasound anisotropy is lower than the anisotropy determined from fibers in paper surfaces. Figure 9 shows the fiber orientation result for two locations within a sheet of each of the restoration papers. Uiryeong-k showed an orientation angle of around 180 degrees (equal to 0 degrees) at both the locations with a high anisotropy at location 1 but a very low one at location 2. The estimated orientation angle indicates that the fibers are oriented in the left-and-right direction from the craftsman's view, corresponding to the motion of the bamboo wire in the manufacturing process; however, the fiber orientation is likely to have occurred partly because of fiber aggregation at location 2. Zangji-k and Yoshino-j showed an orientation angle of around 90 degrees, that is, the back-and-forth direction, with a high anisotropy for the former and a reasonably high one for the latter. Commonly, in the traditional Japanese method, double-layered sheets are formed. The first thin layer is formed on a bamboo wire by pouring out a small quantity of fiber slurry from a tub over the near edge of the wire to the craftsman and then allowing the extra slurry to flow down over the far edge or again toward the near edge and over it. In this thin layer, the fibers tend to be oriented in the back-and-forth direction. Zangji-k was manufactured in this manner, and the wire-side of the sheet was photographed. Yoshino-j is characteristic of Japanese paper and is considered to show high anisotropy in the back-and-forth direction. However, the anisotropy was rather low presumably because the addition of a large quantity of rice powder particles to the slurry disturbed fiber orientation in the slurry stream on the tilted bamboo wire.

CONCLUSION

Image analysis using FFT was demonstrated to be applicable in determining the fiber orientation angle and anisotropy. The binarization process of the micrograph images of the paper surface and precise calculations of the average Fourier coefficients as an angular distribution by linear interpolation were developed in this research. This method was applied to digital optical micrographs and scanning electron micrographs of paper. A laboratory handsheet showed a very low anisotropy, indicating random orientation. Copier paper showed a low anisotropy corresponding to the manufacturing conditions customized for its use. Japanese paper showed a higher anisotropy than wood-containing paper. Korean and Japanese papers manufactured using traditional methods and used for restoring ancient documents showed their own characteristic orientation behavior in accordance with the motion of the bamboo wire. The original objective of examining the fiber orientations of paper surfaces in a nondestructive manner was achieved. This method is expected to be utilized for the nondestructive testing of ancient and historical papers to determine the extent of fiber orientation and the methods of papermaking involved.

ACKNOWLEDGEMENT

This research was partially supported by Fukutake Foundation for Promotion of Culture (2003).

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LITERATURE

Abe, Y. and Sakamoto, A. (1991): Measurement of the Z-direction profile of fiber orientation in paper by laser diffraction, Japan Tappi J. 45(6), 694.

Abe Y., Todoroki, H., Takeuti, N. and Sakamoto, A. (1995): Measurement method of fiber orientation on paper surface, Japan Tappi J. 49(5), 849.

Asplund, G. and Norman, B. (2004): Fiber orientation anisotropy profile over the thickness of a headbox jet, J. Pulp Paper Sci., 30(8): 217

Chinga, G., Gregersen O., and Dougherty B. (2003): Paper surface characterization by laser profilometry and image analysis, Microscopy and Analysis (UK), 96, 21

Chinga, G. (2004): Detailed Characterization of Paper surface structure for gloss assessment, J. Pulp Paper Sci., 30(8): 222

Erikkila, A.-L., Pakarinen, P. and Odell, M. (1998), Sheet forming studies using layered orientation analysis, J. Pulp Paper Canada 99:1, 81

Fiadeiro, P.T., Pereira, M.J.T., Jesus, M.E.P. and Silvy, J.J. (2002): The surface measurement of fibre orientation anisotropy and misalignment angle by laser diffraction, J. Pulp Paper Sci. 28:10, 341.

Fujita, M., Kajita, H., Maekawa, T. and Saiki, H. (1995): Evaluation of particle orientation by the Fourier transform image analysis, J. Soc. Mat. Sci., Japan 44:498, 267.

Habeger, C. C and Baum, G. A. (1987): The use of microwave attenuation as a measure of fiber orientation anisotropy, Tappi 70(2), 109.

Kim, H.S. and Pourdeyhimi, B. (2001): The role of structure on mechanical properties of nonwoven fabrics, International Nonwovens J., Summer, 32.

Murata, K. and Fujita, M. (1999): FFT-estimation of fiber orientation on wood fiberboard, J. Soc. Mat. Sci., Japan 48:1, 77.

Niskanen, K. Kajanto, I. and Pakarinen, P. (2001): In "Paper Physics", Chapter 1, "Paper structure", Vol 16 of the Papermaking Sci. and Tech. Series, TAPPI press, Atlanta.

Niskanen, K.J. and Sadowski, J.W. (1989): Evaluation of some fibre orientation measurements, J. Pulp Paper Sci. 15(6): 220.

Osaki, S. (1987): Microwaves quickly determine the fiber orientation of paper, Tappi 70(2), 105.

Sakai, K. (2003): In "Introduction to digital image processing", CQ publishing, Tokyo, p.161.

Scharcanski, J. and Dodson, C.T.J. (1999): Local spatial anisotropy and its variability, J. Pulp Paper Sci. 25:11, 393-397.

Scharcanski, J. and Dodson, C.T.J. (1996): Texture image analysis for paper anisotropy and its variability, Appita 49(2), 100.

Thorr, F., Adolphe, D. and Drean, J. Y. (1997): Study of nonwoven mass reorganization under tensile stress thanks to a new optical sensor and image analysis, Sensors and Actuators, A62, 565.

Waterhouse J. F. (1994): Ultrasonic testing of paper and paperboard: principles and applications, Tappi J. 77(1): 120.

Waterhouse J. F. and Barrett, T. D. (1991): The aging characteristics of European handmade papers: 1400-1800, Tappi J. 74(2): 207 Yang, C.F., Crosby, C.M., Eusufzai, A.R.K. and Mark R.E. (1987): Determination of paper sheet fiber orientation distributions by a laser optical diffraction method, J. Applied Polymer Sci. 34(3), 1145.

Yuhara, T., Hasuike, M. and Murakami, K. (1991): "Fibre orientation measurement with the two-dimensional power spectrum of a high-resolution soft X-ray image", J. Pulp Paper Sci., 17:4, J110.

Equations

$$F(k_x, k_y) = \sum_{y=0}^{y=N-1} \sum_{x=0}^{x=N-1} f(x, y) \exp\left\{-i\frac{2\pi}{N}(k_x x + k_y y)\right\}$$

$$(k_x = 0, 1, ..., N-1; \quad k_y = 0, 1, ..., N-1)$$
(1)

$$P(k_x, k_y) = \left| F(k_x, k_y) \right|^2 \tag{2}$$

$$q(\theta) = \sum_{r=0}^{N/2} P(r,\theta)$$
(3)

$$A(X,Y) = A(r\cos\theta, r\sin\theta) = (1-d_x)(1-d_y)A(x_n, y_n) + d_x(1-d_y)A(x_{n+1}, y_n) + (1-d_x)d_yA(x_n, y_{n+1}) + d_xd_yA(x_{n+1}, y_{n+1})$$
(4)

$$\overline{A(\theta)} = \left(\frac{N}{2} - 1\right)^{-1} \sum_{r=2}^{\frac{N}{2}} A(r\cos\theta, r\sin\theta)$$
(5)



Fig. 1 Low-angle illumination with a transparent plastic cone of a digital microscope.



Fig. 2 Micrograph taken with a digital optical microscope (a), binary image (b), and power spectrum (c).



Fig. 3 Schematic diagram of the calculation of mean amplitude for each radial direction.



Fig. 4 Fiber orientation distribution and elliptic approximation (left) and its representation as a function of angle θ (right).



Fig. 5 Representative digital microscope images, the corresponding binary images, FFT spectra, and overall fiber orientation distributions with elliptic approximation for four types of paper.
From the top, the samples correspond to the laboratory handsheet, copier paper, Japanese paper, and wood-containing paper. The minor axis of the ellipses represents the major orientation direction.



Fig. 6 Fiber orientation angle and anisotropy determined by FFT image analysis of paper surface images taken with a digital microscope.



Fig. 7 Fiber orientation angle and anisotropy determined by FFT image analysis of paper surface images taken by a SEM.



Fig. 8 Anisotropy of fiber orientation determined by FFT image analysis compared to ultrasound anisotropy.



Fig. 9 Fiber orientation angle and anisotropy at two locations, denoted in parentheses, within a sheet of restoration paper.