FIBER ORIENTATION DISTRIBUTION OF PAPER SURFACE CALCULATED BY IMAGE ANALYSIS

Toshiharu Enomae
Assistant Professor
enomae@psl.fp.a.u-tokyo.ac.jp

Yoon-Hee Han
Ph.D. Candidate

Akira Isogai
Professor

Paper Science Laboratory, Department of Biomaterial Sciences
Graduate School of Agricultural and Life Sciences
The University of Tokyo
JAPAN

ABSTRACT

Anisotropy of paper is an important parameter of paper structure. Image analysis technique was improved for accurate fiber orientation in paper surfaces. Image analysis using Fast Fourier Transform was demonstrated to be an effective means to determine fiber orientation angle and its intensity. Binarization process of micrograph images of paper surface and precise calculation for average Fourier coefficients as an angular distribution by interpolation developed were found to improve the accuracy. This analysis method was applied to digital optical micrographs and scanning electron micrographs of paper. A laboratory handsheet showed a large deviation in the average value of fiber orientation angle, but some kinds of machine-made paper showed about 90 degrees in the orientation angle with very small deviations as expected. Korea and Japanese paper made in the traditional ways showed its own characteristic depending on its hand making processes.

KEY WORDS

Fourier transform, Japanese paper, Korean paper, fiber orientation distribution, fiber orientation intensity

INTRODUCTION

Pulp fibers take a variety of spatial configuration in paper and its alignment is an important aspect of paper structure. Statistically, fiber alignment is defined as a fiber orientation distribution as a function of angle θ when the machine direction of a web or sheet is set to $\theta = 0$. Fiber orientation occurs due to a flow of pulp suspension including the turbulence level and orienting shear, so the flow condition may alter it through web or sheet thickness and across the wire plane. Fiber orientation is important because it affects greatly physical properties like anisotropy in strength, drying shrinkage and wet straining, and further two-sidedness in the case its variation of in-plane orientation through sheet thickness present [1].

To determine fiber orientation, there are several methods developed [2]. Anisotropy in mechanical properties like tensile strength and elastic modulus, elastic modulus calculated from velocity at which ultrasound travels in paper and apparent density of paper are easily measured and indicates anisotropy well, Structural properties like diffraction [3,4] or reflection [5] of light particularly with a laser beam, dielectric permittivity of microwave [6], X-ray diffraction also can be an appropriate parameter for anisotropy.

Some researchers applied image analysis for purposes like this. Scharcanski and Dodson [7,8] used a local image gradient of all pixels for images by β-radiography and light transmission. They estimated orientation angle as a direction to maximize the total of length of gradient vectors projected to its direction.

Also in textile and nonwoven fields, there are researchers who tried to determine fiber orientation. Kim et. al [9] recorded video images of thermally bonded nonwovens from polypropylene fibers during tensile deformation and calculated changes of fiber orientation distribution function by image analysis. They revealed that fiber reorientation progress during elongation more remarkably in the cross direction than in the machine direction and it depends on the anisotropy of the structure and the bond pattern. Thorr et. al [10] designed a sensor capable of measuring locally the mass per unit area of nonwoven geotextiles with illumination of an integrating sphere. They exhibited that the orientation distribution curve corresponded well to the vertical orientation in progress of fibers during a tensile test of a needle-punched nonwoven.

FIBER ORIENTATION DETERMINED BY IMAGE ANALYSIS

Fourier transform

Fourier Transform (FT) is useful for detecting periodicity in signals and images. To paper, it is applied for investigating wire mark, flocculation size, etc. Supposed an image $f(x, y)$, where f means a gray level at position (x, y), Equation (1) expresses $F(kx, ky)$, namely, FT of $f(x, y)$. Equation (2) expresses Inverse Fourier Transform (IFT).

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

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

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

$$(x = 0,1,\cdots,N-1 \quad y = 0,1,\cdots,N-1)$$

Fiber orientation distribution by Fourier Transform

Image analysis is a powerful tool for determining fiber orientation. Major direction of fibers was determined following the next steps.

Firstly, micrographs captured by several methods mentioned in the experimental section as a 256 gray level image or one converted from 24 bit color images were trimmed to a size of 1024 by 1024 pixels or 512 by 512 pixels (**Fig. 1a**, for example) to minimize improper shading in the peripheral. Secondly, the images were binarized using a dynamic threshold method of simple moving average (**Fig. 1b**). In this method, white (level 255) or black (level 0) of every pixel was judged by comparing to its surrounding pixels in the 41 by 41pixels block. Moving average method used can correct shading of images taken under inhomogeneous illumination.

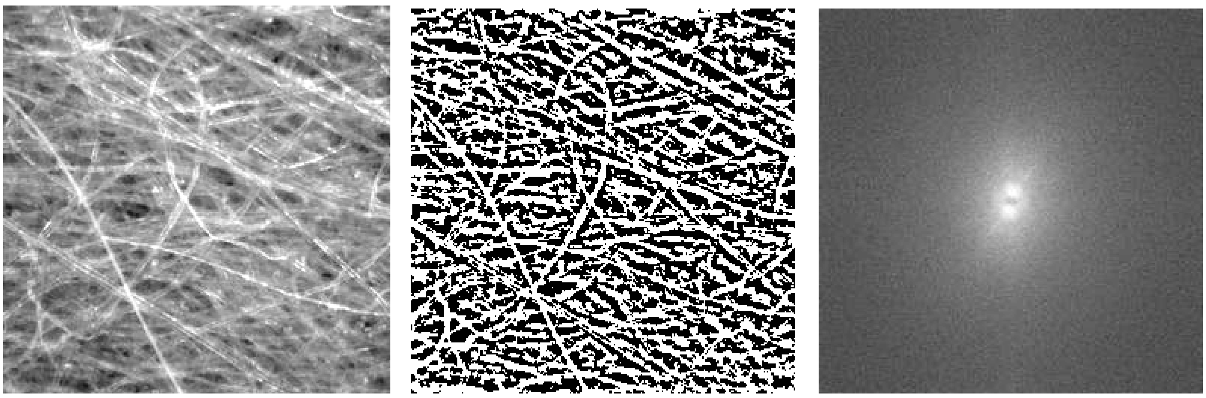

Fig. 1 Micrograph with digital optical microscope (a), binary image (b) and power spectrum (c)

Additionally, this way of binarization can extract edges of fibers out of focus under top fibers in focus or even in whole out-of-focus images. Binarization was performed using a shareware application, PopImaging V.3.1, Digital being kids, Co. Ltd., Japan. Thirdly, for Fast Fourier Transform (FFT) was computed with these binary images using an application of Visual Basic 6.0, Microsoft Corp. developed by the authors. **Figure 1c** is an example of a power spectrum. The FFT routine was programmed following a general textbook.

In the process of determining fiber orientation from the Fourier transformed image, amplitude of Fourier coefficient was added in the radius direction from the origin, that is, the center of the image toward the peripheral and its mean was determined from 0 to 180 degrees of center angle θ. But, a problem occurs in this process. This addition was found to be not as easy as we expected because each position meaning frequency of the Fourier coefficient in the XY coordinates cannot be easily converted to the corresponding point in the polar coordinates exactly. If one draws a radius of a given center angle from the XY coordinate origin, the radius passes just through some positions but mostly only near the positions. Then, interpolation was applied in the following manner.

Suppose amplitude of a Fourier coefficient $A(X, Y)$ at a position (X, Y) in the XY frequency space (See **Fig.2**). We designed the calculation method that amplitude $A(X, Y)$ at that point with center angle θ and radius r is given by Equation (3). Then, mean amplitude $\overline{A(\theta)}$ in every direction of center angle θ was calculated according to Equation (4) and was defined as the fiber orientation distribution in this work.

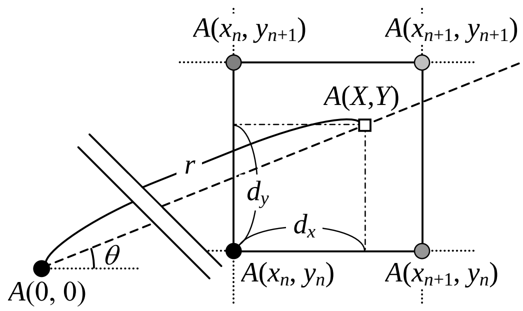

Fig. 2 Schematic diagram of calculation of mean amplitude every radius direction

$$\begin{aligned} A(X,Y) &= A(r\cos\theta, r\cos\theta) \\ &= (1-d_x)(1-d_y)A(x_n, y_n) + d_x(1-d_y)A(x_{n+1}, y_n) + (1-d_x)d_y A(x_n, y_{n+1}) + d_x d_y A(x_{n+1}, y_{n+1}) \end{aligned} \quad \cdots(3)$$

$$\overline{A(\theta)} = \left(\frac{n}{2} - 1\right) \sum_{r=2}^{\frac{n}{2}} A(r\cos\theta, r\sin\theta) \quad \cdots(4)$$

Adding starts with $r = 2$ in this equation and not with $r = 1$ or $r = 0$. the reason is as follow: at $r = 0$, $A(0, 0)$ meaning an average of gray level of all the pixels in the original micrographs, is the amplitude under consideration and it is common to every radius direction. Brightness, that is, mean gray level of a micrograph is not really related to fiber orientation, therefore $A(0, 0)$ should not be included. Even at $r = 1$, $A(0, 0)$ is partially included in the calculation without θ=0 or 90 degrees (Fourier coefficients at 180 and 270 degrees are all the same with those at 0 or 90 degrees, respectively). $A(0, 0)$ is usually by far larger than other amplitudes and affects the mean amplitude too much. To eliminate this adverse effect, the calculation was programmed to start with $r = 2$.

$\overline{A(\theta)}$ is an irregular function with some peaks at angle θ perpendicular to fibers alignment direction. This curve was approximated to an ellipse. FFT and then inverse FFT after low-pass filtering in frequency domain (frequency n>3 cut off) were performed with the curve, initially. This process is equivalent to an approximation to a sine curve. The maximum value *a* and minimum value *b* and center angle α, that is, θ at $\overline{A(\theta)} = b$ were adopted as lengths of major and minor axes and the orientation angle for elliptic parameters. **Figure 3** demonstrates an ellipse determined in this way. This result corresponds to the sample data of Fig.1. This procedure is simple and the FFT routine can be used also for this purpose, but far from exact elliptic approximation in the case of higher orientation intensity. Another elliptic approximation with a nonlinear least square method of realizing more suitable fitting is now under programming.

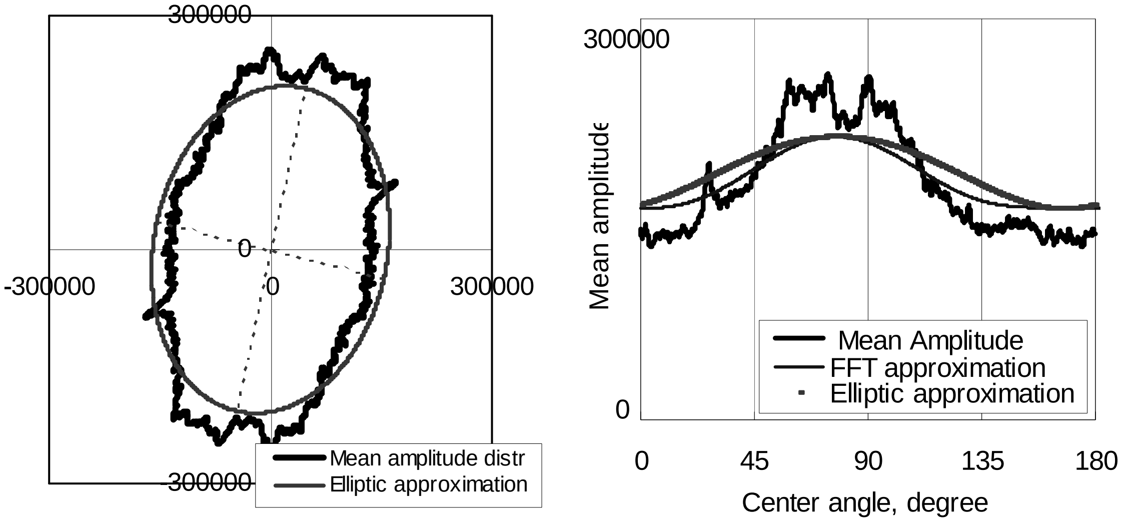

Fig. 3 Fiber orientation distribution and elliptic approximation (left) and its representation as a function of center angle θ.

EXPERIMENTAL

Paper samples

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

Additionally, restoration paper for ancient arts and documents was used. they were Korean paper (Hanji) made in the traditional way that an extra slurry flow out in all directions over the edges of a bamboo wire frame (Iryong-k) and made following the traditional Japanese way that an extra slurry is thrown away over the edge of the opposite side of the craftsman (Iryong-j) both in a craft center in Iryong, Korea. Sample Zangji-k was also made in the traditional Korean way in a craft center of Zangji, Korea. Sample Yoshi-j is Japanese paper made with rice powder in Yoshino, Nara, Japan.

Method of acquiring surface image

Digital Microscope DG-2, Scholar Co. Ltd., Japan was used to acquire reflected light images of paper surfaces at 100 times magnification. Specimens on a scanning stage were illuminated at a low-angle with light which is composed in such a way that light beams coming from six point sources arranged equilateral-hexagonally are concentrated in a cone-shaped plastic to emphasize mountains and valleys on surfaces. Five images were captured from each of evenly spaced 9 locations of top, middle and bottom by left, center and right of a sheet. Individual images were 1792 by 1184 pixels in size, but their central 1024 by 1024 pixel regions corresponding to

1.66 by 1.66 mm^2 were subjected to FFT followed by image analysis. Micrographs taken with a scanning electron microscope, S-4000, Hitachi, Japan were also used as an image object for the image analysis. Specimens were cut to an area of 8 by 4 mm^2 from distant 2 locations within a sheet. Micrographs were taken at 40 times magnification using an image capture device to a size of 2392 by 1942 pixels and trimmed afterwards to 2 images of 1024 by 1024 pixels corresponding to 1.27 by 1.27 mm^2 for image analysis.

Restoration paper samples were photographed with the digital microscope at two locations about 100mm apart within a sheet. Five micrographs were taken at each location and subjected to image analysis. In the images, the bottom side is the craftsman's side.

Gloss and ultrasound velocity anisotropy

As a method other than image analysis for determining fiber orientation, anisotropy in gloss and ultrasound velocity were chosen. Velocity of ultrasound traveling in a sheet is known to be proportional to a square root of elastic modulus as shown by Equation (5).

$$E = \rho C^2 \qquad \cdots(5),$$

where E, ρ and C are dynamic elastic modulus in GPa, apparent density of sheet in g/cm^3 and ultrasound velocity in km/s. Measurement was made every 30 degrees in in-plane angle from the long side direction. Simply, the ratio of the highest velocity to the lowest velocity was calculated as orientation intensity.

Gloss anisotropy is assumed to be associated with surface roughness anisotropy primarily due to surface geometry generated by fiber orientation although its formulation is difficult. Specular gloss was measured at 85 degrees of incident and reflected lights with a glossmeter, GM-268, Konica Minolta, Japan. In-plane angle was likewise every 30 degrees. The ratio of the highest gloss to the lowest gloss was calculated as gloss orientation intensity.

RESULTS AND DISCUSSION

Figure 4 shows images of paper surfaces photographed with the digital microscope for four kinds of paper samples in the left column and their binary images, FFT power spectra and fiber orientation distributions with elliptic approximation. Each sample image in this figuree was selected from 30 or 40 (for a handsheet) images of each paper sample so that it came closest to its mean value of orientation angle and intensity. **Table 1** shows the statistic results on fiber orientation angle. The laboratory handsheet was evaluated to have some orientation angle statistically because every calculated angle falls between 0 and 180 degrees, but the confidence level was large enough to judge it is almost random. Perfectly random orientation would give the confidence level of about 16 and 29, depending on the sample numbers, for the digital microscope and SEM images, respectively. The orientation angle of other samples shows about 90 degrees with the confidence level of as low as 1 for digital microscope images. On the other hand, the SEM images show different orientation angles, presumably because small areas were photographed. The value of the confidence level of the copier paper for SEM was rather high (meaning large deviation) because of one exceptional image present with a different orientation angle caused by a large fiber. If this is ignored, the result is consistent with that for digital microscope. **Table 2** shows the statistic results on fiber orientation intensity determined by image analysis, specular gloss and ultrasound velocity. For every method, the intensity had very low values of the confidence level (meaning stable data). Image analysis provided larger intensity values than the other two methods for the laboratory handsheet. But, overall, if the intensity is less than 1.10, the orientation is almost random; and if more than 1.20, it is clear and intense. Anisotropy of gloss in specular gloss was similar to that determined by image analysis. That of ultrasound velocity

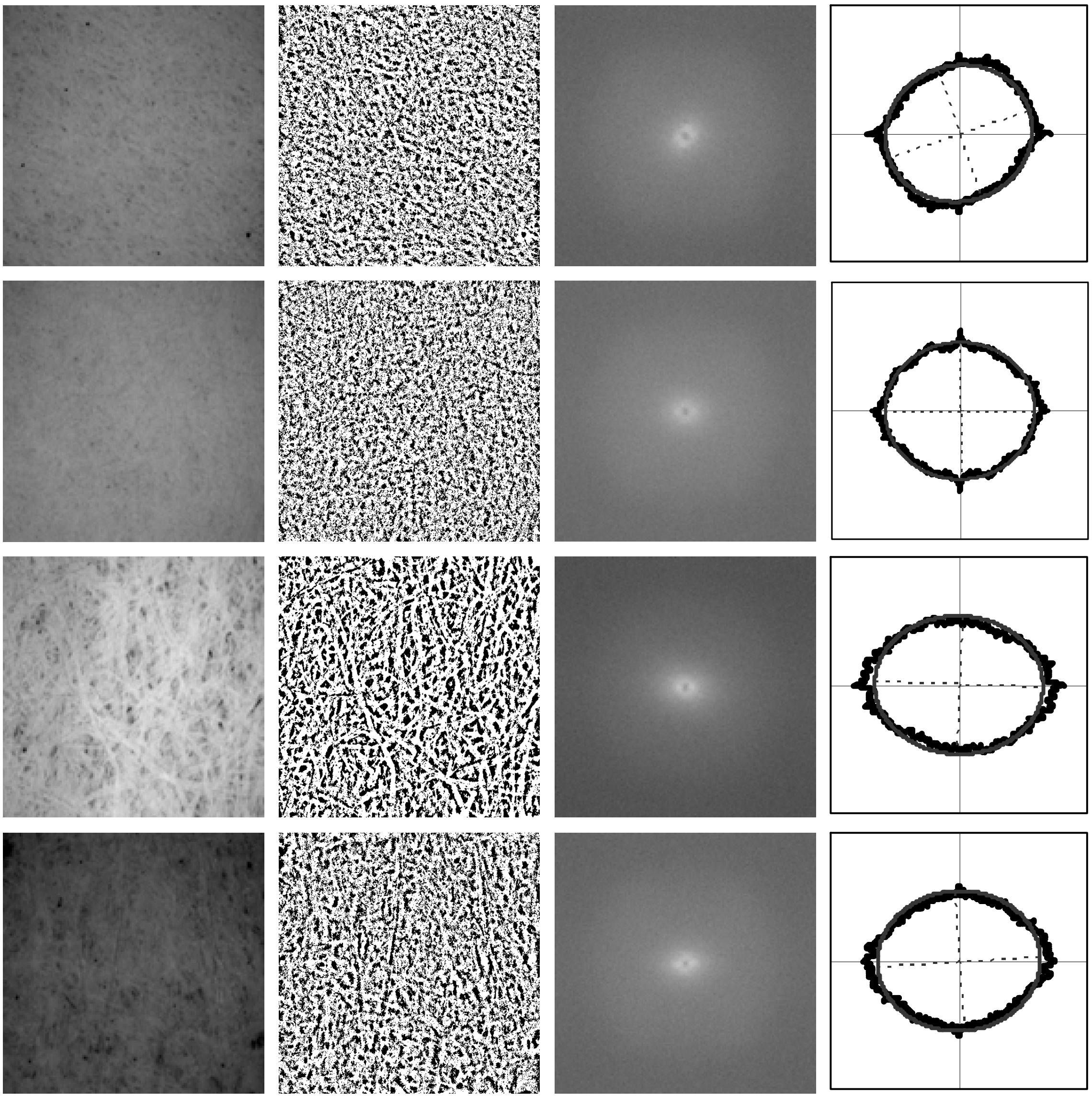

Fig. 4 Digital microscope images, binary images, FFT spectra and fiber orientation distributions with elliptic approximation of each representative specimen for four kinds of paper.

TABLE 1 ORIENTATION ANGLE DETERMINED BY FOURIER IMAGE ANALYSIS

	Laboratory handsheet	Copier paper	Japanese paper	Wood-containing paper
Image analysis				
- Digital microscope				
Average, degree	109	91	88	93
95% confidence level, degree	7	1	1	1
- Scanning Electron Microscopy (SEM)				
Average, degree	115	84	95	Not measured
95% confidence level, degree	20	14	4	Not measured

TABLE 2 ORIENTATION INTENSITY DETERMINED BY VARIOUS METHODS

	Laboratory handsheet	Copier paper	Japanese paper	Wood-containing paper
Image analysis				
- Digital microscope				
Average	1.09	1.09	1.21	1.15
95% confidence level	0.01	0.00	0.01	0.01
- Scanning Electron Microscopy (SEM)				
Average	1.07	1.07	1.15	Not measured
95% confidence level	0.02	0.01	0.01	Not measured
Specular gloss of 85°				
Average	1.00	1.10	1.17	1.25
95% confidence level	0.07	0.02	0.04	0.02
Ultrasound velocity				
Average	1.00	1.63	1.85	2.15
95% confidence level	0.02	0.01	0.00	0.04

resulted in higher values than the other method. Ultrasound does not travel along the sheet surface, but along the inside and the reverse side. Therefore, if fiber orientation of a sheet is varied from one side to the reverse side, it follows that the velocity distribution does not correspond to the fiber orientation in the surface of one side.

Table 3 shows the image analysis result of the restoration paper. The orientation angle of three samples resulted in high values (large deviation) of the confidence level, but the rest showed very low values, that is, very stable. Iryong-k at location 1 showed strong intensity with an orientation angle of 173 degrees. This means that fibers were oriented in the horizontal direction from the view of the craftsman. Iryong-j and Zangji-k showed high orientation intensity in the direction of back and forth. Yoshi-j is characteristic of Japanese paper and was considered to show high orientation intensity in the back and forth direction, but the intensity was rather low, presumably rice powder particles present in the fiber network disturbed fiber orientation practically and reduced the contrast of the original micrograph pictorially.

TABLE 3 FIBER ORIENTATION ANGLE AND INTENSITY OF HANDMADE SHEETS OF KOREA AND JAPAN

Kind of paper	Iryong-k		Iryong-j		Zangji-k		Yoshi-j	
Location	1	2	1	2	1	2	1	2
Orientation angle								
Average, degree	173	87	94	109	105	99	95	85
95% confidence level, degree	4	53	4	29	19	5	4	5
Orientation intensity								
Average	1.26	1.10	1.23	1.16	1.19	1.19	1.13	1.12
95% confidence level	0.04	0.04	0.04	0.04	0.02	0.06	0.03	0.02

CONCLUSION

Image analysis using Fast Fourier Transform was demonstrated to be an effective means to determine fiber orientation angle and its intensity. Binarization process of micrograph images of paper surface and precise calculation for average Fourier coefficients as an angular distribution by interpolation developed in this research were found to improve the accuracy. This method was applied to digital optical micrographs and scanning electron micrographs of paper. A laboratory handsheet showed a large deviation in the average value of fiber orientation angle, but some kinds of machine-made paper showed about 90 degrees in the orientation angle with very small deviations as expected. Korea and Japanese paper made in the traditional ways showed its own characteristic depending on its hand making processes.

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