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A Discrimination Method for Paper by Fourier Transform and Cross Correlation*

ABSTRACT: A non-destructive method for discriminating between different types of paper has been proposed, using image analysis, Fourier transformation, and cross-correlation matching. A fast Fourier transform (FFT) is used to extract the periodicity in the structure of paper that results from the manufacturing processes. The light-transmission images of the paper to be Fourier transformed are obtained from a flatbed image scanner. The similarity between the power spectrum of the FFT of the sample and that of a reference is quantified using a cross-correlation matching method. An advantage of using frequency analysis is that periodicity can be detected even if the sample is damaged or is printed on. The technique works on samples as small as 2 cm^2.

KEYWORDS: forensic science, questioned document, image analysis, paper formation, Fourier transform, cross-correlation, non-destructive testing

We have previously proposed two methods for identifying paper: comparison of the pulp fibers (1), and analysis of filler and pigment using various analysis techniques (2). Various other analysis methods have also been proposed, which have focused on filler and/or additives: Barnard et al. (3,4) used scanning electron microscopy X-ray microanalysis, Foner et al. (5) and Sugita et al. (6) used X-ray diffraction, Andrasko (7) used Fourier transform infrared spectroscopy, and Ebara (8) and Sugita (9) used pyrolysis gas chromatography. These methods are quantitative, but they are destructive because the samples have to be cut before they are analyzed. In addition to these methods, non-destructive techniques using macro- or microscopic observations were proposed by Sugita et al. (10, 11). The defect of these methods is their inability to quantify the degree of similarity. In summary, no method has yet been proposed for paper discrimination that is both non-destructive and quantitative.

The processes used to manufacture paper produce several kinds of periodicity. These processes include dewatering on a forming wire, vacuuming with a suction roll, and drying with canvas fabric pressed against a dryer cylinder. Because different papermaking companies use different machine combinations, each paper has its own combination of periodicity. Even if the raw materials are very similar for similar end products, the marks produced by different machine combinations would provide clues for discriminating between different manufacturers.

There have been many studies concerning paper "formation" metrics (12) and its frequency analysis (13–19). In this work, we fast Fourier transformed (FFTed) the light-transmitted image of a paper sample to extract its spatial characteristics, and calculated the degree of similarity between the power spectra (PS) of the FFT of the image and that of a reference image. This method is both non-destructive and quantitative.

This article on discrimination of paper by frequency analysis is introductory and still being developed. There are still several problems; the sample amount and condition needed are limited, and error ratio is not negligible yet.

Equipment and Software

Flatbed image scanners are used widely for the analysis of paper because they are inexpensive, readily available, and provide precise spatial alignment. We used a model with a light transmittance unit (GT-9000WIN with GTA4FLU, Epson Corp.) coupled to an IBM-PC/AT-compatible computer (VT513S, Seiko Epson Corp.; Pentium 133 MHz CPU, 32 MB RAM) to capture the light-transmission paper images. Its light source consists of a rare-gas fluorescence lamp, whose spectrum is different from that of natural light (20). The scanner was controlled by the software that was supplied with the scanner (Epson Scan! II 32 V2.00J). The images were saved in TIFF5.0 format. All the specimen paper sheets were put on the scanner surface with their "wire" sides face-down against the glass. The "wire" side is the side that shows wire-mark clearer.

The spatial resolution of the images was 400 dpi (one pixel was 63.5 μm) and the images had dimensions of 512 × 480 pixels (i.e., 32.5 mm horizontally and 30.5 mm vertically). The light intensity was stored using 256 gray levels (8 bit), with the exposure of the scanner set to "0" (Fig. 1). In Fig. 1 we can see cloud-like struc-

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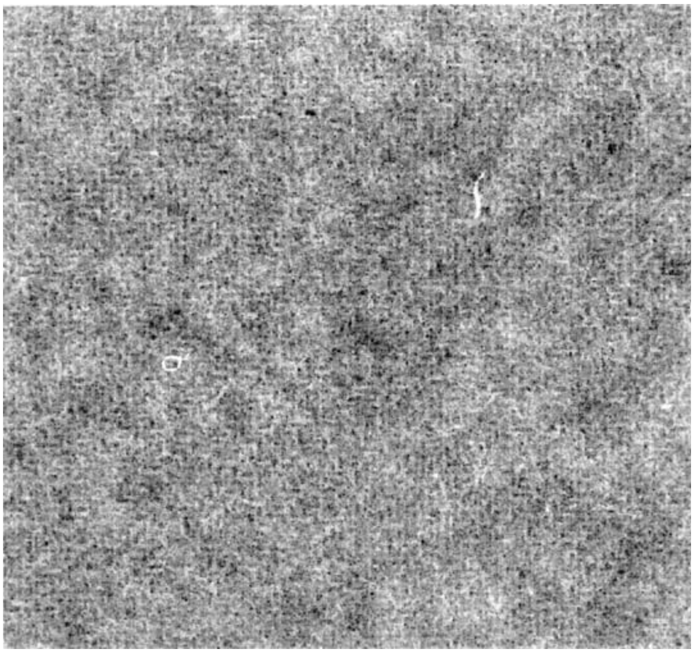


FIG. 1—*Light transmitted image of paper. In dimensions of 32.5 mm × 30.5 mm.*

tures—called "formations"—in the image that result from the combination of many waves of different wavelength.

The image analysis software used was Dot Analyzer DA-5000S V4.00 (Oji Scientific Instruments, Inc. Hyogo, Japan) with its optional package for performing two-dimensional (2-D) FFTs. Excel 97 (Microsoft Corp.) was used for various computations using its built-in functions and our own Visual Basic macros.

Frequency Analysis

The 2-D FFT was applied to a 256 × 256-pixel area of the images to obtain a 2-D PS (Fig. 2). The location of a peak in the PS indicates its wavelength and the direction of its repetition axis (Fig. 3). The distance between a peak and the center of the PS is inversely proportional to its wavelength. For example, if the distance was n pixels, the peak corresponds to a wavelength of 25.4/400 × 256/n mm. Low-frequency components appear near the center of the PS, whereas high-frequency components appear towards the perimeter of the PS. That also means that all the peaks on a concentric circle have equal wavelengths.

As mentioned above, the direction of the peak from the center of the PS corresponds to the direction of the axis of the repetition. For example, when the peak is in the upper-right area of the PS, the repetition goes from top-right to bottom-left. The brightness of the spot (i.e., the strength of the peak) is proportional to the intensity of the wave in that direction on the paper. Therefore, PS figures show the lengths and directions of waves, which are present in the paper.

Similarity Calculation

A cross-correlation matching method has been adopted for the quantitative calculation of similarity between the PS of the sample and that of the reference samples. Please note that in this article the PS is given in dimensionless units (i.e., not using logarithms). The equation used is the sum of the multiplication of the power at the same coordinate of the sample and reference, divided by the lengths of the vectors:

$$E = \frac{\sum\sum f(i,j)\cdot g(i,j)}{\sqrt{\sum f^2(i,j)}\cdot\sqrt{\sum g^2(i,j)}}$$

$$f(i,j) = g(i,j) = 0, \text{ if } \sqrt{i^2 + j^2} \leq 10$$

where

$f(i,j)$: power of reference file at (i,j)
$g(i,j)$: power of sample file at (i,j)
i, j: coordinate in the PS in x and y directions, respectively (both integers with a value between 1 and 255).

Wavelengths longer than approximately 1.6 mm (i.e., $\sqrt{i^2 + j^2} \leq 10$) have been eliminated for the correlation calculation. The outstanding periodicity of a wire is around 0.5 mm, and the power

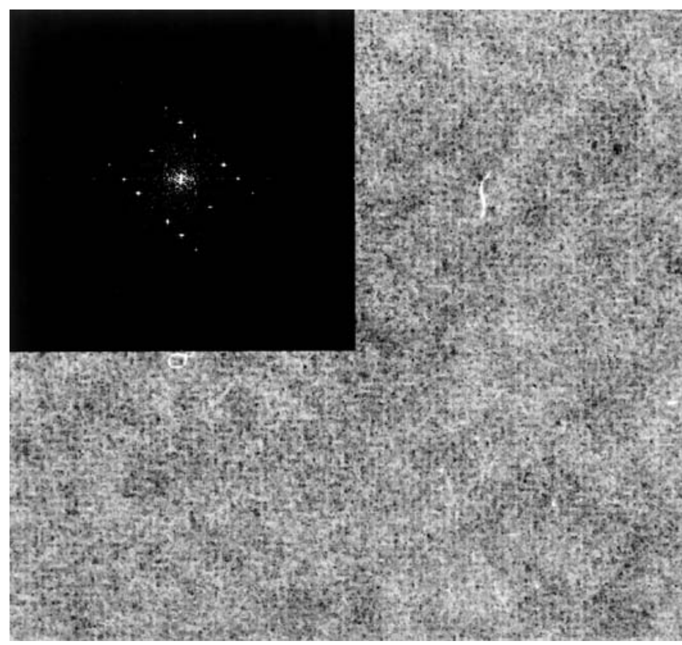


FIG. 2—*2-dimensional Power Spectrum image of the light transmitted image of paper. A frequency analysis of 2-dimensional fast Fourier transmission has been applied onto the specimens of 256 × 256 pixels of Fig. 1.*

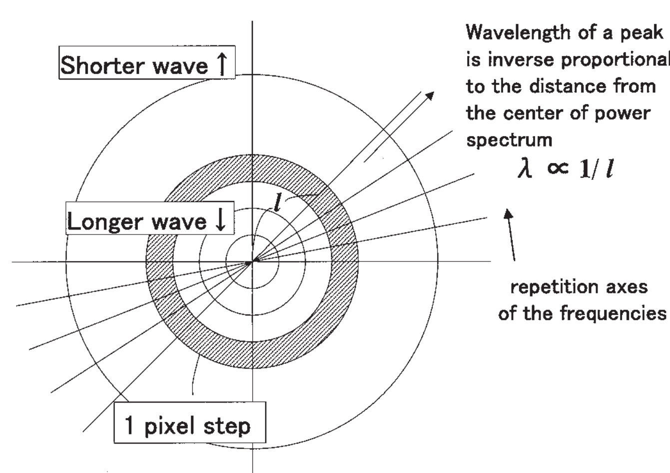


FIG. 3—*How to read FFT power spectrum.*

of longer wavelengths is considerably larger than that of shorter ones. When $E = 0$ there is no similarity between the sample and the reference, and when $E = 1$ the two are identical or analogous.

Results and Discussion

Test Case 1: Hand Sheets (21)

The methodology was tested by applying it to hand sheets that were prepared using different commercially available forming wires. Hand sheets were prepared using a round-type paper machine according to the Japan Industry Standard method. The pulp used was bleached hardwood kraft pulp at 450 mL of Canadian Standard Freeness. The target basis weight was 45 g/m^2.

To leave different wire marks on the hand sheets, five different commercially available wires were used. The wires were put on regular round-type wires stuck with packing tape. The dimensions of the fragments of wires were 8 cm $\times$ 6 cm; their meshes were 45–180 strands/in. Figure 4 shows light-reflected images of these wire surfaces. Table 1 lists the basic properties of the wires that were used for papermaking. Each forming wire produced four hand sheets, one as a "sample" and the other three as "references."

Figure 5 shows light-transmission images of the hand sheets made from these forming wires. Notice that each paper looks different, and has mirror-reflected images of its original wires. Reference PS files were prepared as follows. Four portions from each of three reference sheets (twelve portions in total) were Fourier transformed and their PS were simply averaged in to eliminate local variation in each sheet (Fig. 6). It can be seen at a glance that the power spectra obtained from the different portions of the same sheet are similar. However, the ordering of the powers is very disparate. Twelve portions were used as references so that a truly representative average was obtained, but this did involve a substantial amount of work.

Sample PS files were prepared as follows. One of the four hand sheets was intentionally crumpled to simulate actual use. Just a single portion in the sample sheets was Fourier transformed. Although

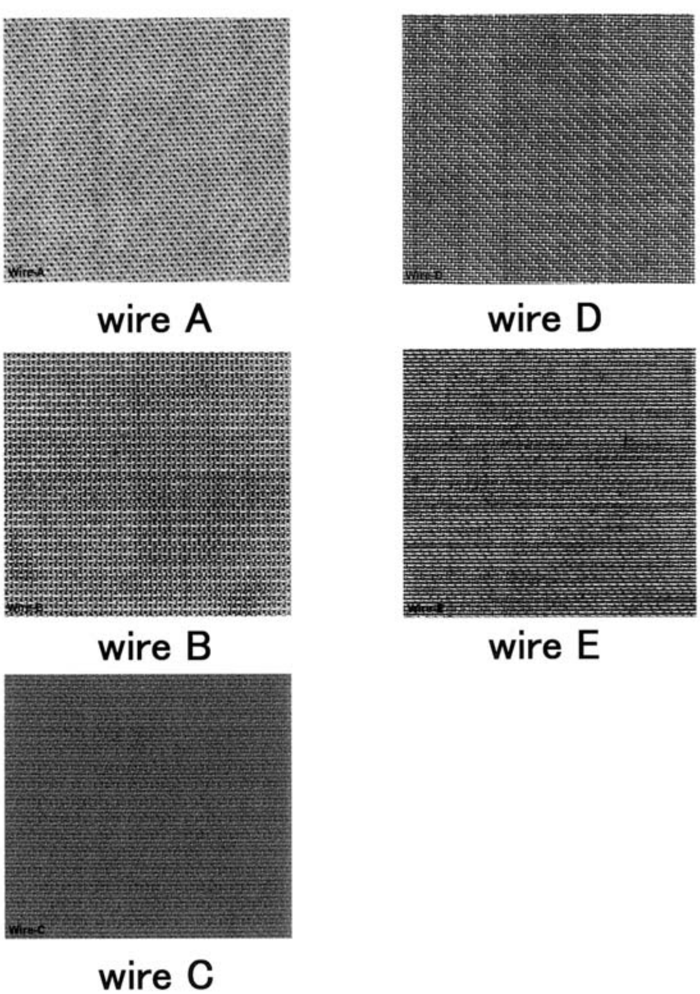


FIG. 4—*Light-reflected images of commercial wires in dimensions of 32.5 mm wide $\times$ 30.5 mm high.*

TABLE 1—*Mesh counts and yarn materials of the forming wires.*

Wire	Warp*	Weft*	Yarn Material
A	60	38~41	Plastic
B	45	32	Bronze
C	60~90	50~52	Plastics
D	65	64	Bronze
E	80	56	Bronze

* Mesh count: strands per inch.

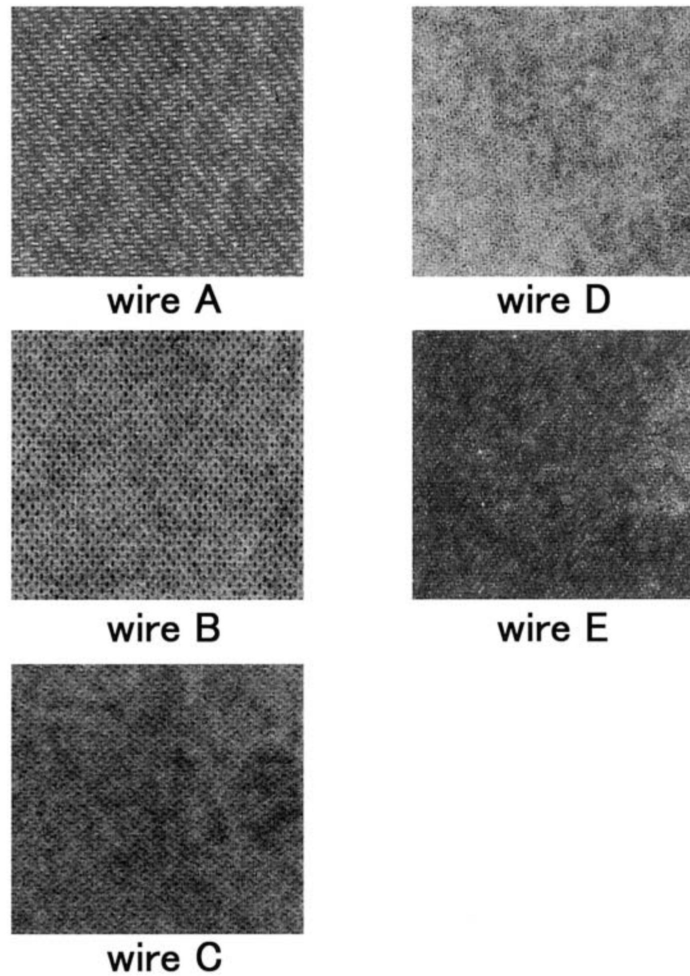


FIG. 5—*Light-transmitted images of hand sheets out of the commercial wires, A thru E, shown in Fig. 4. The dimensions were of the same size with that of the wires. Note that each image shows mirror-reflected wire-mark of its original wire.*

a greater number of portions in a sheet increased the precision of the discrimination, we tried a small number of samples to simulate the conditions of actual use.

The similarity of each of the five sample files to all of the five reference files was then calculated using cross-correlation (Table 2). All five sample files showed the highest similarity when they were compared with the reference files that were prepared with the same wire.

The cutoff value for similarity is not defined clearly in this article—only relative similarities between samples and references were used to compare which reference is most similar to the sample. In addition, the advantage of frequency analysis is that the similarity can be judged correctly even if part of a sheet of paper to be analyzed is destroyed or creased.

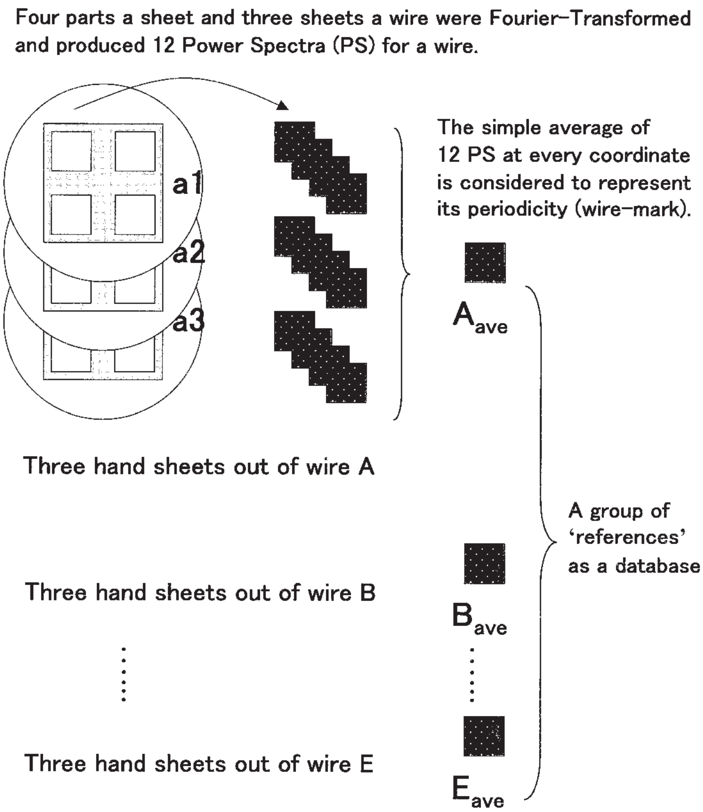


FIG. 6—*Method of determine "reference" power spectra as a database.*

TABLE 2—*Cross correlation calculation; similarity 'E' between the power spectra of the "samples" and of the "references"—the case of hand sheets.*

Sample Reference	A	B	C	D	E
a	0.9432	0.0008	0.0023	0.0037	0.0053
b	0.0022	0.8777	0.0059	0.0078	0.0098
c	0.0012	0.0013	0.4884	0.0085	0.0076
d	0.0018	0.0016	0.0049	0.6871	0.0069
e	0.0015	0.0011	0.0037	0.0078	0.1572

NOTE: Each sample (written in lower case letters; a through e) showed the highest similarity (i.e., the cross correlation E) when it was compared with the reference (written in upper letters; A through E) prepared with the same wire (underlined pairs; a is with A, b is with B and so forth).

Test Case 2: Application to Photocopier Paper (22)

Photocopier paper is being increasingly used, not only for black-and-white copying (as in the past) but also for color photocopies and for laser and inkjet printers. We collected as many commercial photocopier papers as we could, i.e., 130 brand names that were sold in 1998.

We applied the methodology described above to samples of twelve brand-name photocopier paper produced by six papermaking companies (A through F). The products were similar, being made of 100% chemical pulp with a basis weight of approximately 64 g/m^2, bleached, and of A4 size (210 $\times$ 297 mm). The differences between them were difficult to determine using existing methods. The basis weight and the thickness of each brand are shown in Table 3.

All twelve photocopier papers were used for the production of "reference" images: four sheets of A1, A2, A3, E1, E2, F1, and F2; three sheets of B1 and D2; two sheets of B2; and one sheet each of C and D1. The set of 'reference' files can be considered as a "database." To make up the reference files, twelve portions from each paper type were Fourier transformed and their PS were simply averaged in to eliminate local variation of each sheet. To make up the sample files, three portions in one sheet were Fourier transformed for the twelve paper types. The PS of the sample files were simply averaged in the same way as for the reference files.

Table 4 shows similarities among the 12 specimens. A larger value indicates a greater similarity between the pair's periodicity. Initially ten of the twelve sample and reference files correctly exhibited the largest similarities when they were correlated with the files obtained from the same paper types. The other two pairs of sample and reference files, however, did not exhibit the same level of similarity. While the similarities among hand sheets were clearer between correct and incorrect pairs, the similarities among the commercial photocopier paper samples were unclear. For example, in the case of reference $A2_{ave}$, the greatest similarity is not seen with sample a2 but, incorrectly, with sample a1. Similarly, sample B1 incorrectly shows the greatest similarity with reference $B2_{ave}$, instead of with reference $B1_{ave}$.

Figures 7–1 and 2 show contrast-equalized inverse-Fourier-transformed images with the top 50 peaks included except for waves that were longer than 1.63 mm (i.e., 10 pixels from the center of the PS). Both images of Figs. 7–1 and 2 (from samples a1 and a2, respectively) have common repetitions of vertical stripes and $+60°$ and $-60°$ waves (Fig. 8–1). Similarly, vertical stripes and waves of $+45°$ and $-60°$ are seen in Figs. 7–4 (sample b1) and 7–5

TABLE 3—*Physical properties of the Photocopier paper employed in this work.*

Brand Name	A1	A2	A3	B1	B2	C	D1	D2	E1	E2	F1	F2
Basis weight (g/m^2)	93	89	91	85	84	92 ± 4	85	85	87	95	90	95
Thickness (μm)	64	64	64	64	67.8	68 ± 3	64	64	64	64	64	64

NOTE: Alphabet stands for a paper mill company.

TABLE 4—*Cross correlation calculation; similarity 'E' between the PS of samples and of references—the case of photocopier paper.*

	$A1_{ave}$	$A2_{ave}$	$A3_{ave}$	$B1_{ave}$	$B2_{ave}$	C_{ave}	$D1_{ave}$	$D2_{ave}$	$E1_{ave}$	$E2_{ave}$	$F1_{ave}$	$F2_{ave}$
a1–5	0.847	0.844	0.717	0.805	0.809	0.535	0.608	0.693	0.651	0.686	0.721	0.778
a2–5	0.812	0.837	0.726	0.756	0.816	0.523	0.587	0.677	0.633	0.661	0.693	0.735
a3–5	0.670	0.679	0.785	0.718	0.701	0.458	0.489	0.458	0.575	0.602	0.631	0.705
b1–4	0.759	0.782	0.737	0.815	0.846	0.515	0.582	0.538	0.657	0.676	0.732	0.771
b2–3	0.741	0.770	0.744	0.767	0.853	0.505	0.587	0.533	0.624	0.666	0.705	0.749
c–2	0.568	0.587	0.538	0.599	0.594	0.881	0.441	0.389	0.481	0.507	0.547	0.595
d1–2	0.679	0.639	0.541	0.657	0.625	0.405	0.856	0.532	0.490	0.509	0.559	0.612
d2–4	0.697	0.627	0.477	0.527	0.523	0.346	0.433	0.920	0.430	0.434	0.461	0.499
e1–5	0.610	0.626	0.598	0.623	0.672	0.408	0.464	0.433	0.869	0.644	0.575	0.603
e2–5	0.675	0.705	0.635	0.710	0.715	0.467	0.506	0.471	0.702	0.875	0.654	0.716
f1–5	0.725	0.743	0.664	0.761	0.757	0.465	0.558	0.508	0.616	0.628	0.867	0.758
f2–5	0.749	0.770	0.699	0.790	0.770	0.507	0.588	0.530	0.629	0.674	0.719	0.833

NOTE: Coefficients underlined are of the same brand names, where each sample (a1–5, …) should show the largest coefficient.
A couple of coefficients in shaded cells are of wrongly identified pairs.
Sample a1–5 showed the largest similarity correctly with reference A1, but A2 showed the largest wrongly with A1 not with A2.
Sample b1–4 showed the largest similarity wrongly with reference B2 not with B1.
Cells in broken lines are of the same paper company.

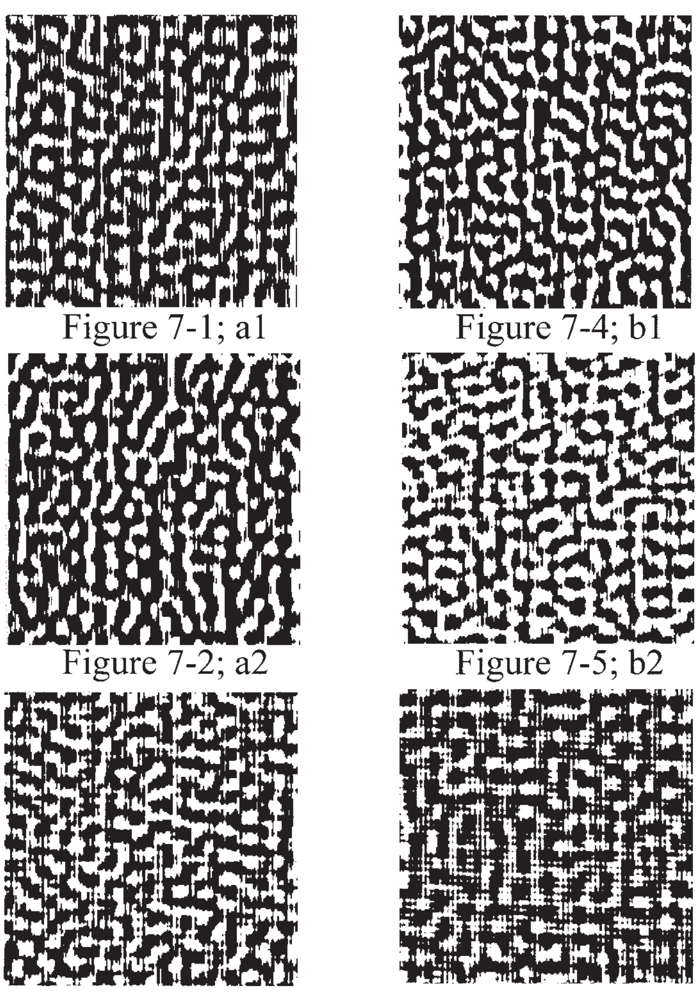


Figure 7-1; a1
Figure 7-2; a2
Figure 7-3; a3
Figure 7-4; b1
Figure 7-5; b2
Figure 7-6; c

FIG. 7-1—*Inverse FFTed images with top 50 power peaks excluding longer waves than 1.63 mm at resolution of 400 dpi (part 1).*

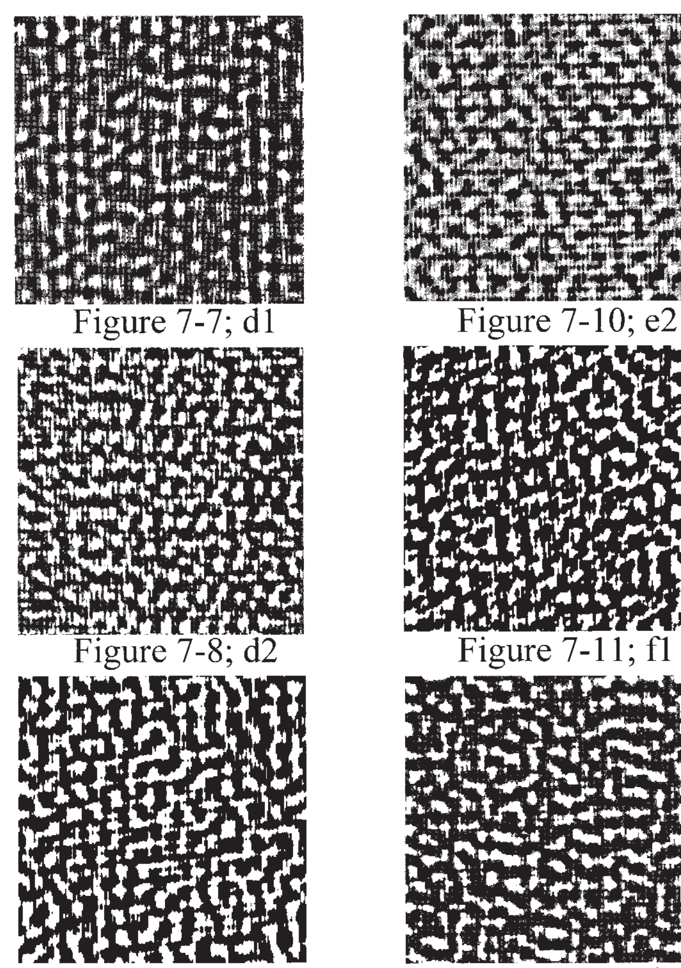


Figure 7-7; d1
Figure 7-8; d2
Figure 7-9; e1
Figure 7-10; e2
Figure 7-11; f1
Figure 7-12; f2

FIG. 7-2—*Inverse FFTed images with top 50 power peaks excluding longer waves than 1.63 mm at resolution of 400dpi (part 2).*

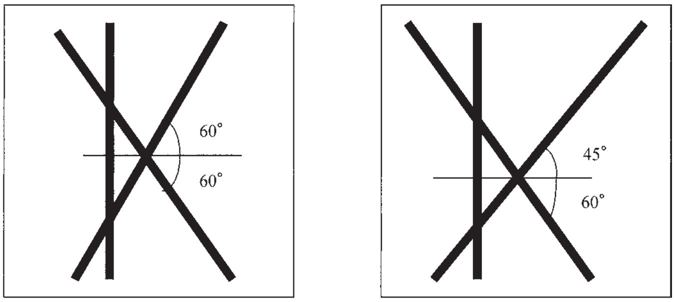


FIG. 8—*Repeating axes commonly seen both in Figs. 7-1 and 2 (Fig. 8-1; left) and both in Figs. 7-4 and 5 (Fig. 8-2; right).*

(sample b2); (Fig. 8–2). From the resemblance between these structures, the pair of a1 and a2 and the pair of b1 and b2 seem to have been produced from papermaking machines with either the same or very similar wires, respectively.

The similarity values are closer in the case of photocopier paper than for the hand sheet discussed in Test Case 1. This is probably because commercial paper exhibits a more complex periodicity, which results from the greater complexity of the papermaking machines. One conjecture is as follows, some photocopier paper with different brand names may be produced by the same machine and, in a special case, identical products may be sold with different brand names, because of a company's sales strategy. As a result, it may be easier to identify the papermaking machine used to manufacture a particular photocopier paper rather than the actual brand name of the paper. Referring to Table 4 from this point of view, the samples of each company resemble each other, or the similarities are closer. In areas within the dotted lines in Table 4, almost all of the similarities of As, Bs, Ds, Es, and Fs are approximately 0.8. Each group in the dotted lines may have been manufactured by the same machine or by a similar combination of machines. One major Japanese paper company is known to use several machines in the production of photocopier paper. Therefore, more sample photocopier brand names have to be examined.

Test Case 3: Examination of Newspaper

Newspaper was also examined using our method of image analysis. Knowing the original place of issue of a newspaper found at the scene of a crime can provide vital evidence regarding the identity and activities of a criminal. In Japan, several major newspapers are delivered countrywide that have nearly the same content, and although their circulation figures are very large they tend to be printed locally. The circulation figures of local newspapers are much smaller, and it is easy to tell the area of origin from a newspaper's characteristic contents. To estimate the delivery area of a major newspaper, the analysis of the paper can be useful because different paper is often used in different news-printing machines in different towns.

We chose four major newspapers (A, B, C, and D) with a national circulation, and picked up specimens every four days during April 2000 (April 1, 5, 9 . . . Apr. 25) that had been delivered in Tokyo. A Japanese newspaper usually has 40 pages or ten sheets a copy. All of the sheets of the specimens were Fourier transformed, and then the periodicity in their PS was compared visually (because numerical grouping was not successful). Table 5 shows graphically the kinds of paper that were used to produce each newspaper each day.

Figure 9 shows the five different PS images that were seen from samples of newspaper "A," which means that five different kinds of paper were used in the production of this newspaper. All the pages from newspaper "A" published on April 1 are of one kind of paper, and the same paper also was used on April 9 and on the subsequent days. On April 5, newspaper "A" was produced using another type of paper. Newspaper "B" on April 1, and newspaper "C" on April 1 and April 5 were printed on the same paper. Each newspaper uses different types of paper from day to day to ensure a stable supply—if the newspaper were to use a single type of paper from a papermaker, the newspaper would not be published if there were problems with the paper supply.

Figure 10 shows a sketch of a newspaper printer. To make up a single newspaper, all the pages are printed at the same time and then they are combined together. There are several paper rolls on a

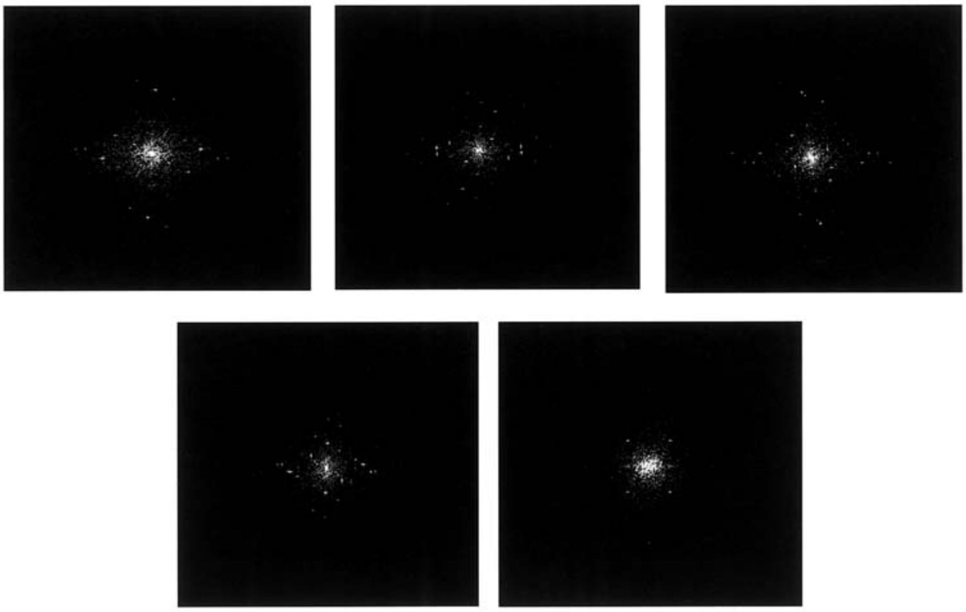
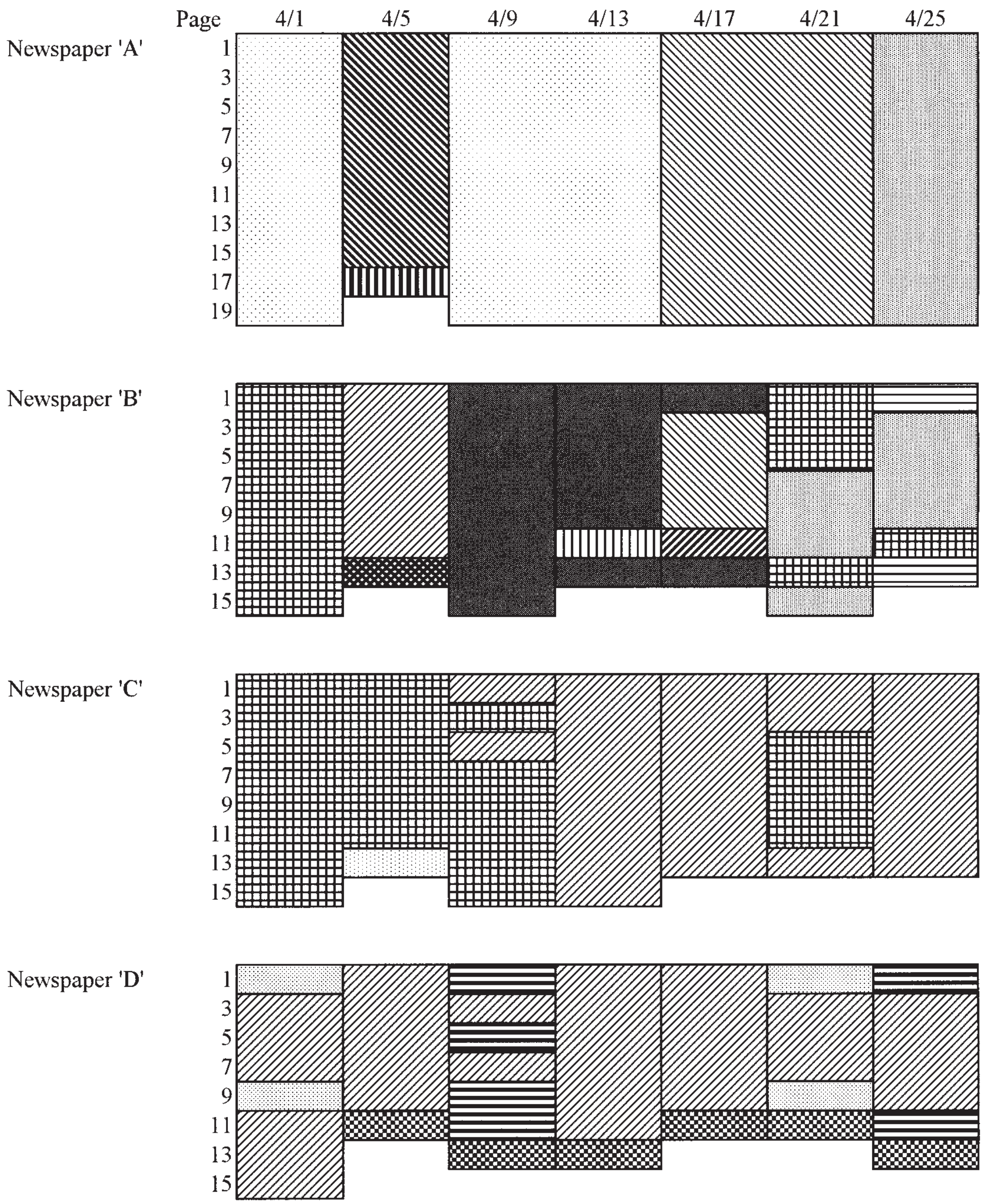


FIG. 9—*Power spectra images of newspaper of brand "A."*

Table 5 The newsprint distribution of each newspaper.



One pattern stands for a kind of paper.
Each Newspaper uses differemt paper in a copy as well as paper from day to day.

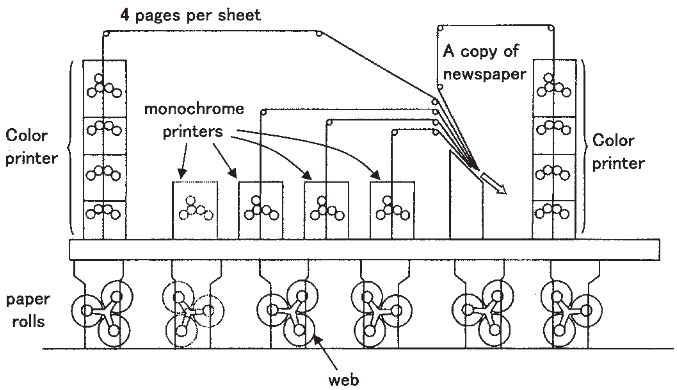


FIG. 10—*Sketch of news printing machine (23).*

newspaper printer, and each roll becomes four pages so that the type of paper for each roll can be chosen freely. Because each newspaper-printing site in Japan uses different types of paper for the same news content, the kind of paper will be a clue to where the newspaper was printed.

In the case of newspaper, we used only the visual comparison of PS because numerical similarity calculations were not successful. This difficulty could be the result of stretching of the wires, which is caused by tension in the driving direction. During the use of forming wires for up to 3–4 months, the wire elongation can be expected. We are currently modifying our discrimination algorithm to overcome these difficulties. Indeed, an improved algorithm that can detect the stretching of these wires may prove helpful in determining the time of production of the paper.

Another reason why this case of newsprint was less successful than the cases of hand sheets and photocopier papers can be considered as follows. In Case 1, i.e., the case of hand sheets, all the sample sheets were made at the same time consecutively. And in Case 2, i.e., the case of photocopier papers, the samples were picked up from realms of each brand name. While in Case 3, i.e., the case of newsprint, each page of a copy of newspaper was (and is still) out of a different roll. Because a copy of Japanese newspaper is printed at the same time and all the pages (i.e., paper sheets) are always of different roll of paper.

Conclusion

A non-destructive method for discriminating between different types of paper has been proposed. The procedure consists of two parts: using a FFT to detect the periodicity in the paper that results from the manufacturing processes, and quantifying the similarity of the PS of the Fourier transform using a cross-correlation matching method.

Application of this method to hand sheets has shown the usefulness of the technique. When applying the technique to commercial photocopier paper, ten out of twelve specimens were matched correctly, whereas two samples (with different brand names) had similar periodicity. We guess that these could have been produced from the same machine. However, more sample photocopier brand names have to be examined.

Application of this method to newsprints was less successful than application to the cases of hand sheets and photocopier paper because each page of a copy of newspaper is printed on a different roll on paper. The paper forming wires become longer while they are used, leaving little different wire marks on the paper.

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