Systematic Analysis of Periodic Variation in Paper Structure

Yong Joo Sung† and D. Steven Keller*
(Received September 17, 2009; Accepted December 8, 2009)

ABSTRACT

Periodic variation of local paper structure was evaluated using two-dimensional fast Fourier transform (FFT) and spectral analysis. Since the periodic variation could originate from various sources and have different magnitudes and patterns depending on the origins, a complete analysis of local paper structure properties such as local grammage, local thickness, local apparent density and surface topography was proposed in this study. For a commercial copy paper, the individual periodic patterns for each local structural property were identified by using inverse FFT spectrums of the filtered spectrum. The spectral analysis of newsprint sample provided the period of variation quantitatively, which was useful in comparing the origins of the individual periodic patterns of the local structural properties.

Keywords: periodic variation, local paper structure, FFT, spectral analysis, inverse FFT spectrum

1. Introduction

The non-uniformity of paper structure, i.e., local variation, has been a major issue in the paper industry due to its great influence on paper quality and the efficiency of papermaking processes. Local variation in paper structure is typical comprised of both stochastic variations and deterministic or periodic variations in the local properties. This reflects the fibrous nature of the web, which is composed of randomly distributed fiber, and consolidation of the web between woven machine fabrics. Because the periodic variation in paper structure can at times be considered a defect in the optical appearance of paper or the print quality,1-3) many investigators have characterized such variations in the local structure (2,4-7). However, since these investigations focused on analysis of periodic variation for only one or two structural properties, e.g., surface topography or optical formation, a complete analysis of each of the local structure properties including local thickness, local grammage, local apparent density and surface topography was examined in detail in this study. Such insights will be valuable in identifying the true nature of a complex structure that may originate from several sources. Characterization of the deterministic patterns within the structure and identifying their origins may then be possible. Therefore, in this work, a systematic
approach to evaluation and determination of periodic pattern in paper structure was carried out.

It is generally accepted that paper and paperboard can have deterministic variations in structural properties derived from forming fabrics, wet pressing fabrics, dryer fabrics, or various types of wet pressing rolls.\(^5,6\) Because this periodic variation can significantly affect end use properties, such as paper aesthetics or print appearance, several studies have explored detection, identification and analysis of periodic pattern.\(^2,7,8\)

The forming fabric (wire) and the wet press fabric and rolls are the usual origins of periodic patterns in paper structure. The various weave patterns and drainage properties of forming fabrics lead to two typical markings which are drainage marking and topographical markings.\(^9\) The water flow channels caused by the opening pattern of the surface of the forming fabric result in deterministic variations in micro scale basis weight and in the distribution of the fines and filler material (drainage marking). In topography marking, the paper or board surface can become embossed with a replicate of the surface sources of periodic patterning in the paper structure; these are the press fabric or the press roll. A press fabric is typically composed of a base layer woven with coarse polymeric filaments and a needled batt layer composed of fine fibers with a diameters of 30 mm. The base layer can have various weaving patterns depending on the types of yarns, which determine its water handling capacity and compressibility.\(^10\) It is these that provide different marking pattern on the wet sheet.\(^11\) The surface properties of the batt layer also have a strong influence on the roughness of the paper, which can result in periodic or stochastic variations in the surface profile.\(^11\)

To increase the efficiency of wet pressing, various types of opening or venting patterns on the roll surface are used. These include grooves, blind-drilled holes, and suction holes. Such open structures on the roll lead to non-uniform pressure on the felt and consequently on the wet sheet. The non-uniformity of the shear force action of the water draining within the wet sheet structure results in suction shell marking and groove marking which produce local variation in paper density.\(^8,12\)

Although such marks can sometimes be easily detected by the unaided eye, it is usually difficult to determine the exact source of the marks, especially for paper and paperboard which has large stochastic variation. For example, poor formation or a rough surface makes such casual assessment quite difficult. Furthermore periodic marks can originate from more than one source. Thus, more detailed information about the local thickness, local grammage, local density and surface topography can improve our ability to characterize periodic marks with greater accuracy and distinguish the exact origin of each component that contributes to a complex periodic pattern.

In this work, maps of the four structure parameters were obtained. The periodic patterns contained within the maps were analyzed using two-dimensional fast Fourier transform (FFT) as given by

\[
F(a,b) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} f(m,n)e^{-j(2\pi/M)am}e^{-j(2\pi/N)bn} \tag{3}
\]

where,

\[
f(m,n) = \text{A function of two discrete spatial variables m and n,}
\]

\[
F(a,b) = \text{The two dimensional Fourier transform of } f(m,n)
\]

The FFT converts spatial domain data, which can be any type of two dimensional matrix such as local grammage distribution map, local thickness variation map, local density map, or surface topography map, to frequency domain data, in which the periodic variations can be easily detected, identified, emphasized and removed.
2. Experimental Methods

2.1 Measurements of mass distribution

Local grammage distribution (formation) maps of the samples were obtained using a storage phosphor b-radiographic imaging system. The paper sample was exposed to b-ray emissions from a \(^{14}\) radiation source backed by a storage phosphor screen that stores a latent image of transmitted radiation. The screen was scanned at 100-mm pixel size using a PhosphorImager\textsuperscript{TM} scanning instrument (Molecular Dynamics, Sunnyvale, CA). The obtained image was calibrated to convert instrument units to actual grammage images, based on a Mylar reference wedge. This system has a linear response to b ray exposure and good sensitivity, i.e. \(\sim 0.1 \text{ g/m}^2\).\textsuperscript{13,14}

2.2 Measurements of the local thickness distribution

The local thickness distribution was measured using the twin laser profilometer (TLP) instrument.\textsuperscript{15} The sample, which was marked with three pinholes for registration with its respective grammage map, was held by the metal frame between two opposing laser sensors. Each sensor detects the surface profile of the paper with a resolution of \(< \sim 1 \text{ mm}\). Combination of both surface profiles resulted in a local thickness distribution map for the sample.

2.3 Measurement of surface roughness

The roughness of each sample for this work was calculated based on line-scanned data using the TLP.

---

**Fig. 1. Evaluation of periodic variation in the local grammage of a copy paper sample**

(a) Local grammage map; mean : 77.3 g/m\(^2\), standard deviation (SD): 8.2, coefficient of variation (COV)(%): 10.6
(b) Fast Fourier transform (FFT) spectrum calculated from the local grammage variation map
(c) Periodic patterns in local grammage map obtained by enhancing the peaks in the FFT spectrum and performing an inverse FFT
(d) FFT spectrum after removing the stochastic variation
(e) Inverse FFT spectrum using the filtered spectrum of (d).
Fig. 2. Evaluation of periodic variation in local thickness of a copy paper sample
(a) Local thickness variation map; mean: 82.5 µm, SD: 7.8, COV(%): 9.5
(b) Fast Fourier transform (FFT) spectrum
(c) Periodic patterns in the local thickness map
(d) FFT spectrum after removing the stochastic variation
(e) Inverse FFT spectrum using the filtered spectrum of (d).

Fig. 3. Evaluation of periodic variation in the local apparent density of a copy paper sample
(a) Local thickness variation map; mean: 936.1 kg/m³, SD: 57.1, COV(%): 6.1
(b) Fast Fourier transform (FFT) spectrum
(c) Periodic patterns in the local apparent density
(d) FFT spectrum after removing the stochastic variation
(e) Inverse FFT spectrum using the filtered spectrum of (d).
Fig. 4. Evaluation of periodic variation in the top surface topography of copy paper sample
(a) Top surface profile; mean is adjusted to zero before analysis, SD: 3.53,
(b) Fast Fourier transform (FFT) spectrum
(c) Periodic patterns in top surface topography
(d) FFT spectrum after removing the stochastic variation.
(e) Inverse FFT spectrum using the filtered spectrum of (d).

3. Results and Discussion

Periodic variations in the local paper structure, i.e. local thickness, formation, local density and surface topography were measured and analyzed by using image analytical techniques. Since these patterns may significantly affect printability, two typical commercial printing papers, wood free copy paper and newsprint paper were selected for examination.

A 30 mm² area of copy paper and an 18 mm² area of newsprint paper were scanned at a 50 mm sampling interval using the TLP. The local thickness map and both surface contour maps for each sample were comprised of 50 mm² elements (pixels), however the pixels in the local basis weight maps and local density maps represented 100 mm² and 200 mm² pixels, respectively.

Fig. 1(a) shows the periodic pattern in local grammage of the copy paper. The 2D-FFT spectrum of the local grammage distribution map is shown in Fig. 1(b). The white dots in the FFT spectrum map represent the intensity of the periodic variation in the original data. The stochastic variation appeared as a continuous speckled pattern decreasing in intensity from the center. The periodic pattern can be easily seen by emphasizing the peaks in the FFT spectrum and performing an inverse FFT as shown in Fig 1(c). In order to identify origin of the periodic pattern in the local grammage map, it was useful to obtain an image
that has only periodic variation. Figure 1(d) shows the FFT spectrum after selectively removing much of the stochastic variation. The inverse FFT spectrum of the filtered spectrum provides the periodic variation image as shown in Fig. 1(e). The same procedures was applied to local thickness, local density, top and bottom surface topography maps for the copy paper sample, and the results of which are presented in Fig. 2~5, respectively.

The distinct periodic pattern on the local grammage map of the copy paper can be observed in the local thickness map and the local density map as well. However, the periodic pattern on the two surface topography maps are a slightly different indicating that the two pattern of surface topography may have different origins or origins other than those contained within the bulk structure.

Since the local grammage and local thickness have a relatively linear relationship, a part of the periodic pattern in the local thickness (certain peaks in the FFT spectrum) is expected to originate from the regular variation in local grammage. However, since the pattern observed in the surface topography also influences the measurement of local thickness, which is composite of the two surface maps, there should then be little difference between the periodic patterns of local grammage and local thickness. This difference resulted in the blended composite pattern for the local density shown in Fig. 3.

Therefore, although there can be various origins of the periodic pattern in the local paper structure and the pattern from different origins can blend together and result in a very complex pattern, systematic evaluation of the local grammage, local thickness, local density and both surface topographies can isolate the various periodic patterns and provide a correct identification.
In the case of the newsprint paper sample, various different periodic patterns can be observed. The distinct periodic pattern in the local grammage map can also be observed in the local thickness, as shown in Fig. 7.

The similarity in periodic variation among local parameters and the periodicity were evaluated by using spectral analysis as shown in Fig. 7 (c), Fig. 8 (c). Each peak in the power spectrum represents the periodicity in each local structure map, and the intensity of each peak indicates the strength of the periodic variation. Therefore a clearer peak indicates a stronger periodic variation. The numbers of each peak represent how often the variation took place, calculated based on the wavelength of the periodic variation. The strong peaks at 1.24 mm and 1.6 mm (1.58 mm for local grammage) were found in both local structure variation maps. These results indicate that specific periodic patterns in the grammage and thickness of the newsprint sample may have originated from an early step in the papermaking process, such as contact with wire fabric, which could affect not only the surface roughness but also the drainage pattern and thus those in the local grammage. Therefore the spectral analysis can be used not only for identifying the exact periodic wavelength but also to identify the specific origin of an observed periodic variation.

4. Conclusions

The various periodic patterns in the paper structure were evaluated using 2D FFT. For a commercial copy paper, different periodic patterns were observed in grammage, thickness, density and both surface topographies, which indicated differences in the origins of the patterns. To identify the origin of the periodic pattern in each local structure map more
clearly, inverse FFT spectrums of the filtered spectrum were obtained by removing much of the stochastic variation in the FFT spectrums. The results demonstrated that systematic evaluation of local grammage, local thickness, local density and both surface topographies can isolate various periodic patterns and provide correct identification of each periodic pattern. Spectral analysis of the newsprint sample also determined the exact wavelength and period of variation, which is useful in comparing the origin of periodic variations in different structural properties.
Literature Cited