Determination of paper formation by Fourier analysis of light transmission images

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Formation is the measure of variations due to non-uniform fibre distribution in a sheet of paper. Paper formation is one of the most important properties of paper and is still difficult to measure. A method for determining this property has been developed. This method, based on light transmission image analysis, uses features of the power spectrum obtained from the Fourier transform to analyse and discriminate between different floc distributions within an image of paper. The method was tested for various furnishes and showed better discrimination between different qualities of formation than the standard formation index.

Keywords
Formation, image analysis, Fast Fourier Transform, power spectrum, light transmission

Many defects and problems such as appearance, opacity, loss of strength and print mottle are related to the small-scale grammage variability present in all papers (*1*). Formation measures the extent and nature of these small-scale variations, which are due to the uneven distribution of fibres in both the plane and the thickness of the sheet of paper, and summarises the information in a form that can be readily interpreted. Modern practices require such analysis to be fast and quantitative.

A sheet of paper can be viewed using a number of techniques: beta radiography, optical imaging, X-radiography and electron beam imaging:

The beta-radiography technique (*2*) provides information on the mass distribution in the sheet. This technique has low internal scatter and a good correlation with the true mass density, but is time-consuming for high grammage sheets.

Soft X-radiography (*2*) has higher resolution than beta-radiography systems and requires less time to acquire the image, but the cost of the equipment is higher.

Optical imaging systems (*2*) are the most popular due to their low cost, simplicity, relative safety and their instantaneous acquisition of data. Even though the measured grammage with this system is dependent on the nature of the test material, the technique can be quite suitable for measuring formation for sheets that are heavily waxed, calendered or optically thin enough.

Several quantitative definitions of paper formation have been developed. The most commonly used formation index is the standard formation number (*1*), which is the standard deviation of local grammage in a small zone of the sheet divided by the mean value of local grammage in the whole sheet. This index has the limitation that formation of different sheets, which appear to the observer to be quite different in formation, may have the same formation number. Dodson (*3*) suggested a new index based on a quantitative relation between a particular sheet and a sheet of ideal formation. Jordan (*4*), using the definition of flocs as regions of heavier than median grammage, calculates for his index the ratio of the sum of floc perimeters for a sample to the size of the sample. If high-frequency information is present in the image then, for a given area of inspection, the measurement of the perimeter will be greater, but the method suffers from the problem that there is no way of calculating the length of the perimeter. The ratio can thus vary from system to system.

The co-occurrence technique (*5*) uses a spatial grey-level dependency (SGLD), and deals with 5 indices that are difficult to relate to the paper properties.

There exist other indexes such as gradient analysis, which offers a basis for analysis by developing a histogram of the image. A uniform image would produce a single vertical line at the origin. The widening of the curve indicates increasing non-uniformity, and the overall shape indicates a degree of 'wildness'. Kallmes (*6*) proposed a quantitative method close to that of Jordan. But most of these indexes suffer limitations, for instance, sheets with quite different formations may have the same index, are more sensitive to the paper structure or they do not give any information on how the flocs are distributed.

In this work, we try to develop a method based on extracting information from the slope of the uni-dimensional function obtained by averaging the power spectrum of the Fourier transform to find a new index of formation, which is more sensitive to local variations in the fibre distribution and is easier to compute than other indexes.

REVIEW OF THE LIGHT TRANSMISSION TECHNIQUE

Beta-radiography is the most accurate technique due to its high correlation with mass, but its disadvantages of high equipment cost and the lengthy exposure time required for experimentation led to a reassessment of the light transmission image analysis method.

The relationship between light transmission through paper and sheet properties may be expressed as follows (*7*):

$$T = b / [a.\sinh(b.S.B) + b.\cosh(b.S.B)] \quad [1]$$

where T is the ratio of transmitted to incident light, S is the scattering coefficient of the sheet (m^2/g), B is the grammage (g/m^2) and a and b are defined by:

$$a = 1/2\,[(1/R_\infty) - R_\infty] \quad [2]$$

$$b = 1/2\,[(1/R_\infty) + R_\infty] \quad [3]$$

where R_∞ is the light reflectivity of an infinitely thick sheet.

Paper scatters light intensely, therefore equation 1 can be approximated as follows:

$$T = 2b\,R_\infty e^{-b.S.B} \quad [4]$$

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This means that the correlation between grammage and light transmission is better for sheets with low grammage. For those with a wide distribution of local grammage, it may be necessary to take images using more than one set of optical parameters (diaphragm, aperture and/or magnification), which are the key elements in the light transmission technique (*7,8*). It has been shown that with a good choice of optical parameters, and suitable software, the results are very positive (*7*).

Even if the measured grammage with the light transmission method is dependent on the nature of the material, the technique can be highly suitable for measuring formation for sheets that are heavily waxed, calendered or optically thin enough.

REVIEW OF THE FOURIER TRANSFORM METHOD

Fourier analysis (FT) is a mathematical technique to decompose a periodic function into a set of sine waves. This technique was generalised first for non-periodic functions and then for periodic or non-periodic discrete time or space signals. The objective was that any function can be expressed as an infinite sum of periodic complex exponential functions. FT decomposes a signal (or image) into complex exponential functions of different frequencies according to the following equation:

$$FT\{f(x)\}=F(u)=\int_{-\infty}^{+\infty} f(x)\, e^{-j2\pi ux}dx \quad [5]$$

The signal, or the function f(x), is multiplied by an exponential term at some certain frequency 'u', and then integrated over all the space. The Function f(x) is multiplied by the sinusoidal term of frequency 'u'. If the signal, or the function, has a high amplitude component frequency 'u', then that component and the high sinusoidal magnitude will coincide, and the product of them will give a (relatively) large value. However, if the signal does not have a frequency component 'u', or is not a major component of the signal, then the product will give a zero or (relatively) small value respectively. This would show that the frequency component 'u' in the signal does not exist or has a small amplitude respectively: it thus means it is not a major component of the signal.

The Fourier transform allows us to convert variations with respect to space or time to a set of sine waves with a range of frequencies from the very low, which correspond to slow variations, to the very high which correspond to signal fine detail.

It is possible to add together a subset, or all the set, of these sine waves to get a filtered version of the signal, or to regain the signal respectively, or to produce as we did in this work a 2-D power spectrum.

The Fourier transform of a given function is complex, so we can separate the Fourier components of F(u) into real and imaginary frequency components:

$$F(u) = R(u) + jI(u) \quad [6]$$

where R(u) is the real part of F(u) and I(u) is the imaginary part of F(u).

The Fourier frequency components can be written in terms of magnitude as:

$$|F(u)| = [R^2(u)+I^2(u)]^{1/2} \quad [7]$$

and phase,

$$\phi(u) = \tan^{-1} [I(u)/R(u)]. \quad [8]$$

The power spectrum is given as:

$$P(u) = |F(u)|^2 = R^2(u)+ I^2(u) \quad [9]$$

For a two-dimensional function f(x,y), for example an image of a paper sample, the two-dimensional Fourier transform is defined as:

$$FT\{f(x,y)\}=F(u,v)= \int\int_{-\infty}^{+\infty} f(x,y)e^{-j2\pi(ux+vy)}\,dxdy \quad [10]$$

where u and v are the frequency components.

The magnitude of the Fourier transform, the phase and the power spectrum are respectively given as:

$$|F(u,v)|= [R^2(u,v) + I^2(u,v)]^{1/2}, \quad [11]$$

$$\phi(u,v) = \tan^{-1} [\frac{I(u,v)}{R(u,v)}], \quad [12]$$

and

$$P(u,v) = |F(u,v)|^2= R^2(u,v)+ I^2(u,v). \quad [13]$$

This procedure can be used to produce a 2-D power spectrum of the image. The 2-D power spectrum contains information on the extent of the variation, the scale of the variation and its directionality.

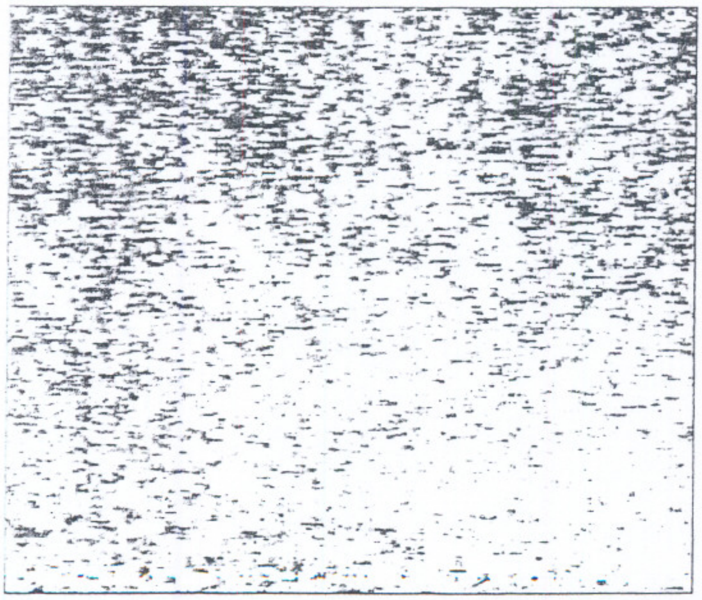

Fig. 1 **Light transmission image of a sheet made from 100% short fibres.**

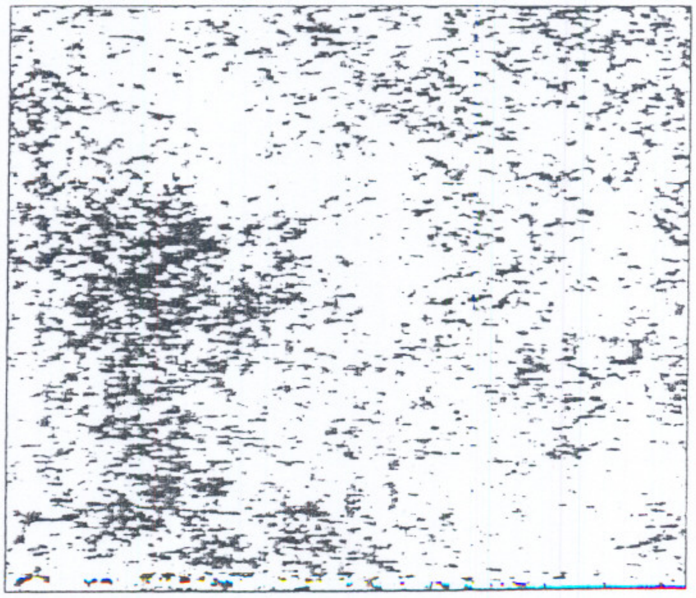

Fig. 2 **Light transmission image of a sheet made from 100% long fibres.**

EQUIPMENT AND EXPERIMENTAL PROCEDURE

Paper for analysis had an area of 6.2 x 6.3 cm^2 and were placed on a light box. A standard CCD (charge-coupled device) monochrome video acquired the image and transmitted it to a computer via an acquisition card. Appropriate software was used for processing the image. With this camera, the image was acquired on a 512 x 512 grid with 256 grey levels, i.e. with a resolution that satisfactorily matched the range generally used.

Several studies (*8*) have shown that the power spectra of natural objects tend to display a functional dependence on the frequency u in the form $u^{-\delta}$, where δ is a real constant. If we consider the image of the paper sheet as a natural texture, then this form should also apply

It has been shown that the coefficient δ is invariant to changes of scale, which allows the incorporation of another parameter u_0 in the functional shape of the spectra in the form $(u/u_0)^{-\delta}$, where u_0 is a scale factor inversely proportional to the scale of the object (*9*).

The divergence at the origin makes this functional dependence difficult to handle, but this can be overcome by assuming a Lorentzian dependence, which is well-behaved at the origin and tends to (u/u_0) as the frequency increases.

It has also been shown (*10*) that the radial profile of the spectra (O) of natural objects tends to radial dependence as:

$$O(\rho) = K / [1+(\rho/\rho_0)^2]^a \qquad [14]$$

where ρ = the radial frequency, ρ_0 = a scale factor, K = a constant and a = an exponent which, when $(\rho/\rho_0)^2 >> 1$ (high frequencies), makes O tend to $(\rho/\rho_0)^{-\delta}$ (with $\delta = 2^a$) and is related to the texture and fractal dimension of the object (*9*).

The method used in this work is based on computing and extracting the information on the radial profile of the power spectrum of images of paper with different formations and evaluating parameters K, a, and ρ_0.

The first step after the image acquisition is to remove the effect of the non-uniform lighting of the light box by a pixel-to-pixel division between the light transmission image of the sheet of paper and the light box image.

The constant K of equation 14 can be eliminated by normalising the zero frequency component of the spectrum to 1 before computing each FT, and then fit the data of the power spectrum plot of each image sheet with equation 14 in order to calculate the parameters a and ρ_0. These parameters are then evaluated for their usefulness in distinguishing different forms of grammage non-uniformity (formation).

The 2-D power spectrum is converted to the 1-D spectrum by calculating the sum of the frequency values in all directions for each radius of the 2-D spectrum. A cut-off frequency is required to compute only the high frequencies (small-scale variations) and also to obtain a good fit with the equation.

RESULTS AND DISCUSSION

Figures 1 and 2 show images of two of the sheets of paper analysed, which were made from different fibre types, and which thus gave different formations. These correspond respectively to handsheets made with 100% short fibres (Sfib) (eucalypt pulp: 1mm average fibre length) and 100% long fibres (Lfib) (pine pulp: 3 mm average fibre length) without any additives or flocculants. Theoretically, the sheets with long fibres should have a poor formation and those with short fibres a good formation.

Overall four handsheets of different fibre compositions (and thus different formations) were made and tested (Table 1). In order to show the sensitivity of the method developed in this work, we also calculated the standard formation number for each of the test sheets of paper.

The standard formation number is obtained by:

$$F.N(A) = \sigma(w_A) / w_M \qquad [15]$$

$$\text{with } \sigma^2 = \sum_i \sum_j (x_{ij}-x_m)^2 \qquad [16]$$

where $\sigma(w_A)$ is the standard deviation of the values of the pixels in zone w_A, w_A = zone of the paper, x_m = the mean value in the w_A zone and w_M = the mean value for the entire image.

The results for the standard formation number and the values of a and ρ_0 are shown in Table 1.

From Table 1 it is seen that the power spectrum index is a much more sensitive indicator of differences in formation than the standard formation number. For instance, sheets made with 75% and 50% long fibre have the same standard formation number, whereas they have quite different power spectrum indices.

For the sheets with 100% and 0% long fibre, where the difference in formation is more evident, it can be seen clearly that the range of difference of the power spectrum index is much higher than that of the standard formation number. This suggests that the power spectrum index will be a sensitive measure of formation. Further work is required to demonstrate the reliability and usefulness of this new method for describing the formation of paper.

CONCLUSIONS

A new method for determining the formation of paper has been developed. This method is based on light transmission image analysis, and uses the features of the power spectrum obtained through Fourier transform analysis.

Continued page 115.

Table 1
Results obtained by the power spectrum index method and comparison with the standard formation number.

	100% long fibre sheet	75 long -25 short fibre sheet	50 long - 50 short fibre sheet	100% short fibre sheet
STANDARD FORMATION NUMBER.	0.0652	0.0517	0.0517	0.0518
a	0.364	0.396	0.423	0.507
POWER SPECTRUM INDEX (ρ_0).	0.0096	0.021	0.0141	0.0282

Table 6
Oxygen transmission rate of filled dispersions on FBB.

Sample	OTR, cm^3/(m^2·d·bar)	Coating, µm
30% talc	710	14
50% talc	>50.000	15
30% clay	480	13
50% clay	36.000	13
30% clay+5% MF	1200	11
50% clay+5% MF	9600	11
30% clay+2% SC	650	14
50% clay+2% SC	17.000	12

reused without severe negative effects, such as a decrease in tensile strength, if the polymer and filler content are low. Repulping conditions and coating composition affect repulpability.

SUMMARY

New water-based coatings and polymerisation techniques are being developed. The coatings presented in this paper are a few examples of the present trend towards environmentally friendly and even bio-degradable water-based coatings. Although biodegradable polymers are designed for extrusion coating or film applications, they show interesting possibilities also as WB coatings. However, their performance has to be improved as biodegradation can only be an additional property and should not affect the cost structure of the coated substrate.

The platey fillers are efficient extenders as far as barrier properties are concerned, due to the increased tortuosity of the coating. Factors such as particle orientation are important for optimal barrier performance. Good grease and moderate water-vapour barrier can be achieved with clays, while talc gave the lowest WVTR. Fillers decrease the flexibility of the coatings. Additives, such as silanes, improved the water and water-vapour barrier of dispersion coatings filled with hydrophilic fillers. Insolubilisers are used to improve water resistance, thus the Cobb values were improved and the water-vapour barrier of clay coatings was also improved. Fluorochemicals can have a positive effect on the barrier performance. Additives, co-binders and co-pigments have a limited effect on coating performance.

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Continued from page 105.

The method was applied to handsheets containing vastly different fibre compositions and thus formations.

Changes in the two power spectrum indexes were high enough to clearly rank formation for the different sheets of paper analysed.

Comparison between the standard formation number and the power spectrum index has confirmed the sensitivity of the new method, which not only provides quantitative formation data, but also information about the average texture of the paper analysed.

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