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INVESTIGATING PAPER STRUCTURE USING IMAGE ANALYSIS

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Abstract

Much has been done in studies of the light and beta-ray images of paper for formation and Mass Density Distribution respectively. This paper presents the comparison of the images obtained by the two methods using random data analysis techniques, such as filter theory, auto-correlation functions, transfer functions and coherence. Only objective measurements will be used so that visual optical illusions will not confuse the results. Types of paper to be studied will include calendered and uncalendered papers.

Introduction

The communications field has led to the development of a whole range of mathematical techniques(9) which makes it possible to distinguish various periodic structures as well as the random stochastic features of a paper sample. These techniques have been applied to the printability of paper by Lyne(1) and Norman(2).

Parker and Attwood(3) published a series of papers describing an ingenious analogue technique for investigating paper structure. Their papers particularly demonstrated how the wire-mark of a sheet of paper may be highlighted using the phase information that can be obtained from some 24 negatives shifted, by one repeat pattern, relative to each other. Very good results were obtained, but the experimental method was laborious.

Direct measurement of the mass density distribution, as defined by Corte[4], now forms a firm basis for investigating the structure of paper. On the basis of theoretical studies, it is also possible to predict the nature of a truly random structure of paper. The necessary experimental studies involve highly specialised equipment, or at least the application of radiographic techniques such as those described by Hellawell[6].

The extent to which light transmission gives any information on mass density distribution (DMD), as defined by Corte[4], is a question of argument. Visual inspection is subject to many optical illusions. However, modern instruments, such as those described by Sealey[5], and Wahren[10], are not subject to these difficulties and new efficient procedures for characterising paper structure are now available.

In fact, formation is measured on a variety of test devices, the most successful of which is probably the Q.N.S.M. meter, or variants on it.

Recent instrumental developments such as the Magiscan, described by Howard[12], make a whole new range of measurements possible. Because a two-dimensional set of data can be handled by computer, not only is speed ensured, but the range of possible calcúlations and modelling is enormously extended.

Theory

The theory used for this investigation is based on the discrete Fourier transform of which the mathematics is adequately described in the book by Bendat and Piersol[7]. The defining equations are:

$$F\ (f(x)) = F(\omega) = \int_{-\infty}^{\infty} f(x)\ e^{-i\omega x} dx \tag{1}$$

$$F^{-1}(F(\omega)) = f(x) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega)\ e^{i\omega x} dx \tag{2}$$

and Parseval's identity:

$$\int_{-\infty}^{\infty} f(x)\ \overline{g(x)}dx = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega)\ \overline{G(\omega)}\ d\omega \tag{3}$$

where the latter equation is required for the power spectrum, auto-correlation and coherence functions.

The application of these equations to finite sets of data requires the use of window functions (Hanning, Hamming or Blackman), filters and ensemble averages.

There are also theoretical problems of accuracy due to blurring and aliasing. Huck et al.[11] discuss blurring of the spatial detail in terms of the limitations caused by the finite spatial frequency response of electro-optical systems. On the other hand, under-sampling of the spatial image results in aliasing. Their calculations substantiate those of earlier workers who found that the blurring of the image was not sensitive to a reasonable spot intensity profile and photo-sensor aperture shape. But some profiles and shapes tend to suppress aliasing better than others. In particular, the Gaussian spot intensity profile of TV cameras is appreciably superior to the circular photo-sensor apertures commonly used in opticomechanical scanners.

To overcome the problems due to lack of phase information, computations are carried out on the power spectra of the sampled data.

Further possibilities arise if the data are treated as a time series and a series of possible (empirical) models may be considered. The auto-regressive model being represented by:

$$x_n = b_1 x_{n-1} + \cdots \cdots + b_r x_{n-r} + a_r \tag{4}$$

The moving average process is:

$$x_n = a_n + C_1 a_{n-1} + \cdots \cdots + C_r a_{n-r} \tag{5}$$

and further functions may be created by combinations of these two forms as well as by considering multiple input systems.

Essentially one is defining some form of transfer function for the process. Parameter estimation is relatively easy and intuitively meaningful if the parameters converge to a constant.

Experimental work

All measurements were taken from contact prints using the procedures described by Tydeman[8,9,14] and Hellawell[6]. One problem that occurred was due to blurring of the images because of poor contact with the flat surface. Wetting was tried, but this gave only moderate improvement. A thicker sheet of foam (18 mm instead of 6 mm) in the `sandwich' was found to be a better way of improving contact. A similar procedure was used for producing both light and beta-ray pictures for analysis on the Magiscan.

Source of sample	Substance g/m^2	Exposure time minutes
UMIST pilot-plant machine	33	33
Conqueror	48	48
Darwhite Bank	42	45
MG ribbed Kraft	78	81

Table 1

Exposure times for different paper samples using beta-ray source

The analysis of the data was carried out using either a Fourier transform computer routine or a coherence function computer routine. In the initial stages, the results were compared with those found using the Q.N.S.M. formation tester. In the latter case, it was feasible to handle only light images.

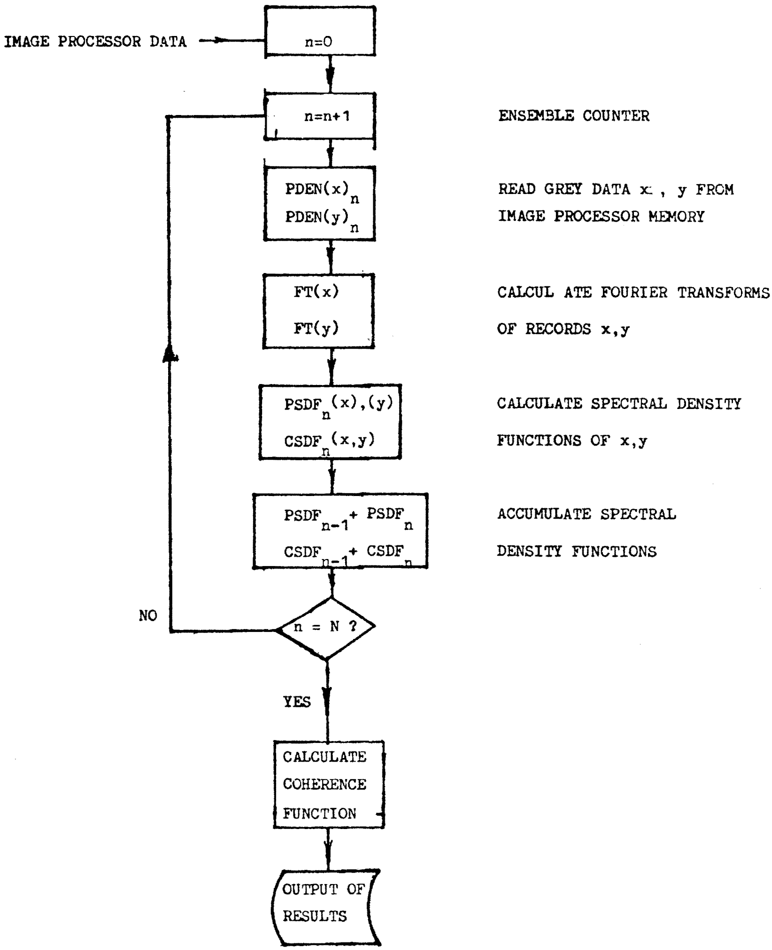

Fig 1—Flow chart of data collection and processing sequence for a coheherence function smoothed over N ensembles

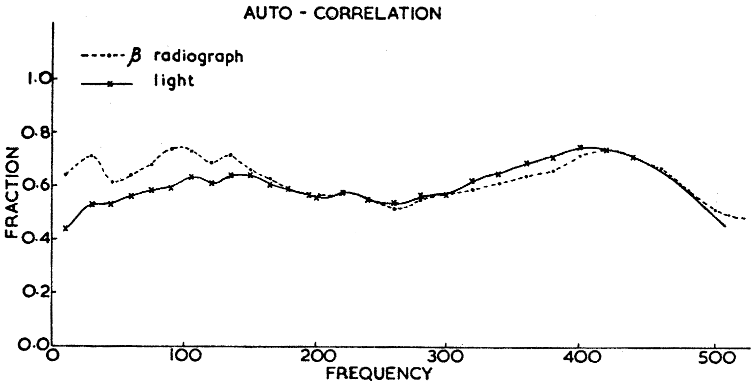

Fig 2—Darwhite Bank, MD

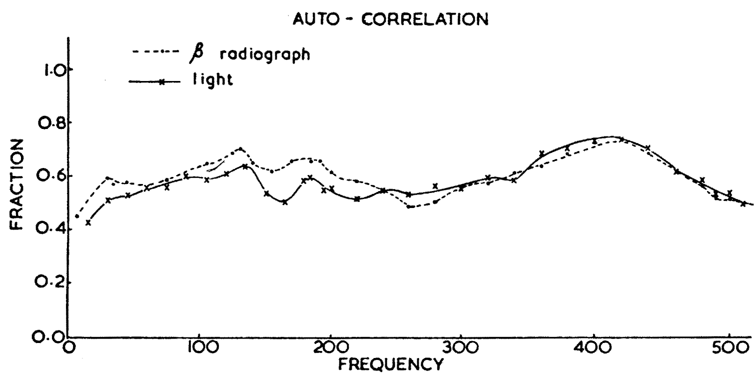

Fig 3—Darwhite Bank, CD

The coherence functions were determined according to the flow diagram given in Figure 1. In each case, the data used were formed from an ensemble of five scans, each scan consisting of 512 data points.

The auto-correlation functions of the Darwhite Bank sample are shown in Figures 2 and 3. This paper gave similar results for beta-radiographs and light contact prints. It is clear that this will not always be so.

The coherence functions determined for a sample of MG ribbed Kraft are shown in Figures 4 - 6. As would be expected, the light-light coherence function, Figure 4, shows strong coherence at a series of frequencies related to the ribbing of the sample. Neither beta-beta nor beta-light images show any very strong coherence at any frequency. This appears to indicate that the samples represent a nearly random distribution at this magnification (one pixel = 0.07mm).

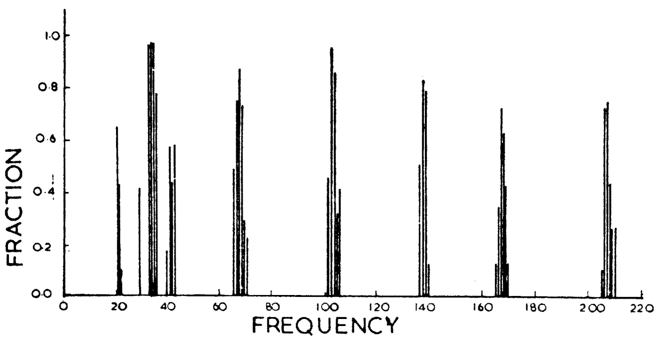

Fig 4—MG ribbed kraft coherence L—L

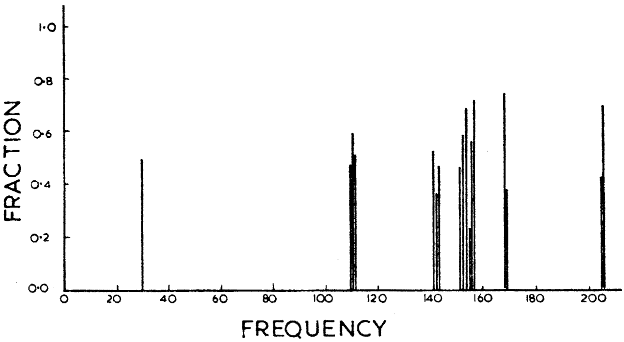

Fig 5—MG ribbed kraft coherence $\beta-\beta$.

The next experimental stage will involve deliberately creating effects which mask the true mass distribution. One such effect is that of calendering, and here it is also possible to demonstrate that soaking and redrying desupercalender the paper. Farebrother[15] pointed this out using incident and transmitted illumination (light) of the same area of a piece of paper in the three conditions (original, super- and desupercalendered).

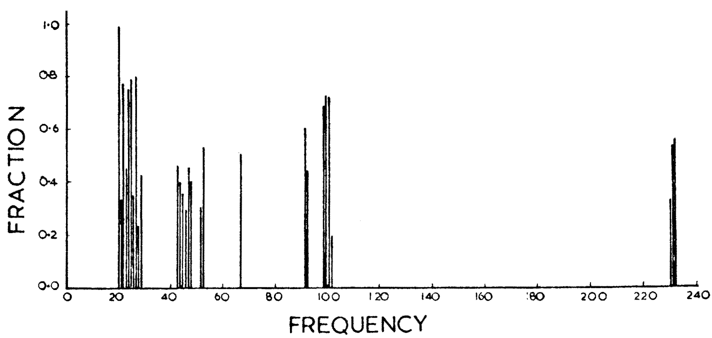

Fig 6—MG ribbed kraft coherence L$-\beta$.

These tests have been carried out on an uncalendered sample made on the UMIST pilot-plant machine. The <u>same</u> field of view was recorded in 3 conditions, off-machine, supercalendered and decalendered, and each condition recorded by contact beta-ray, contact light, macro (incident) and macro (transmitted).

Conclusions

It is clear that visual interpretation of paper structure is subject to many problems due to masking of the underlying structure by the optical properties of cellulose. The beta-radiograph gives more precise information on the detailed structure of paper, but is limited and time-consuming in its practical application. The modern image analyser makes a significant contribution to the speed with which analyses can be carried out, as well as widening the scope of the kind of techniques that can be used to solve problems.

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Transcription of Discussion

Discussion

Panel Discussion following papers presented by Dr. Jordan, Prof. Kropholler and Dr. Taylor.

Dr. B. Jordan

I have a question for Prof. Kropholler. Several years ago Rosenfeld[1] published a note in which he claimed that if one worked with Fourier transforms locally in texture analysis then the edge effects were so pronounced that it made the Fourier or power spectrum useless as a local image-segmenting technique. Hence he favoured run-length statistics. Do you agree with this?

Prof. H. Kropholler

I agree with the comments that you just made. We are not seriously using Fourier techniques, in texture analysis.

Dr. L. Eriksson, STFI, Sweden

I have a question regarding sample preparation. Fibres are three-dimensional in terms of curl. Presumably during analysis the fibres are stationary and thus restrained in some way by external forces. How is sample preparation carried out so as to reflect the true curl?

Dr. B. Jordan

We use a projection technique. There is the underlying assumption that a fibre with say, helical structure is not straightened by squashing it down onto a plane, it will maintain curliness. A straight fibre on the other hand will remain straight on projection.

Mr. B. Klowak, American Can Corporation, Wisconsin, USA

I understand that Dr. Jordan used a proportionality with length to estimate fibre weight. I would like to ask why he did not use a proportionality to area?

Dr. B. Jordan

That is a good question. Actually we have used both methods and there is no great difference.

We have also used, as I mentioned, a method where we take a calibration curve of weight as a function of length.

Mr. B. Radvan, Wiggins Teape, UK

Dr. Jordan, the histograms of radii of curvature which appear in your contribution always had a high population at low radii which you have ascribed to kinks. Do you think this could be used as a measure of damage to the fibres?

Dr. B. Jordan

Yes. There is a great deal of information in these histograms and what we have to do is to find appropriate weights between the high frequency and the low frequency contributions to try to extract something meaningful. Obviously, there is added information if you used both the curvature and the curl. The question remains: what is the paper-making significance of the added information, and is it worth the extra effort? This is the subject of our activities at present.

Dr. C. J. Taylor

We also use curvature measurements similar to those described by Dr. Jordan. We have found that this allows us to differentiate between asbestos and other types of fibres by using syntactic analysis of the resulting histograms.

Prof. K. I. Ebeling, Helsinki University of Technology, Finland

I would like to ask what resolution is possible with the technique. Could you for example analyse the effect of strain on bonded area response, particularly with respect to the effect on the centre area of a bond?

Dr. B. Jordan

The largest problem is one of getting an appropriate image. This is always a problem in image analysis.

I think we have enough contrast to look at local deformations at bond sites, but we have not done it at present.

session 7 discussions

Dr. M. B.Lyne, Paprican, Canada

Many people could be considering the purchase of an image analyser. It would be of interest to know what hardware is required with the analytical equipment that you have described today in order to guarantee inter- and intra-laboratory agreement. In particular, reproducibility of the detection criteria and sample illumination are required.

Dr. B. Jordan

For print quality applications, this is adequately discussed in our paper in Tappi[2].

Illumination is important for fibres also, though not as critical as one might suppose.

Dr. C. J. Taylor

There is generally a better chance of getting good agreement between different sites if the image analysis method used represents some physical model of the subject under consideration. In other words, sample-related techniques are likely to lead to a failure to agree. For example, specific effects or tricks are difficult to reproduce.

Prof. H. Krophollor

I would add that the problems of repoducibililty are even present within one laboratory. On texture-type problems it is imperative to have some calibrating sample included with the samples. Work on fibres can be easier since dyeing the fibre can often result in enough contrast. The physical characteristics that one is looking for can be simpler.

Dr. C.J. Taylor

With some types of image grey-level thresholding can be applicable to asbestos fibres. The problem with this technique is that it is totally variable and different answers are obtained on different occasions since even automatically self-adjusting systems have considerable arbitrariness.

The model we have used supposes a consistently lower optical density related in a linear fashion and a measurement of that is made. The results on the final count don't alter under an order of magnitude change in the illumination on the slide.

Dr. B. Jordan

In situations where the signal - to-noise ratio is very critical then the precise grey-level threshold can be very important. However, in most situations a response plateau is reached, and large changes of illumination are possible without any significant effect on the results.

Dr. C. J. Taylor

Certainly in our experience edges are rarely sharp enough in microscope images and I would have expected that a change in threshold would be expected to give a significant change in the fibre width that you observe.

Dr. B. Jordan

This can be a problem, but the threshold setting that we use is the mid-point of the edge and thus symmetrical broadening from whatever cause, such as the optics, will not have much effect. We have, to date, found reasonable reproducibility over many samples.

Mr. A. de Ruvo, STFI, Sweden

What kind of TV camera is recommended for use on printability studies, where grey-scale measurements are all important.

Dr. C. J. Taylor

We always use a Chalnicon tube because in practice all other tubes are fragile. It has high resolution on near-linear intensity response, and good sensitivity. If you are interested in looking at complete images with a wide intensity range, and you need information from the low intensity areas without saturating the high areas, then a Vidicon with $\gamma = 0.7$, whose response slopes off at high levels, might be more appropriate.

Prof. P. Luner, ESPRI, USA

Returning to the question of the move away from using Fourier transforms to describe structure, is there any problem with the type of signal and its processing or does the problem lie in the paucity of information gained?

Dr. B. Jordan

The computational demands for handling the grey-level occurrence matrices and other real space statistics are just as large as for the Fourier transform. The problem with the Fourier transform lies in its local application and in the presence of edge effects. The finite Fourier transform assumes that the signal is reproduced over and over again outside the sampling region. This small sampling causes errors, as pointed out by Rosenfeld.

Dr. C. J. Taylor

From our experience of using Fourier methods, even when they are not applied locally, the Fourier transform of anything looks much like the Fourier transform of anything else.

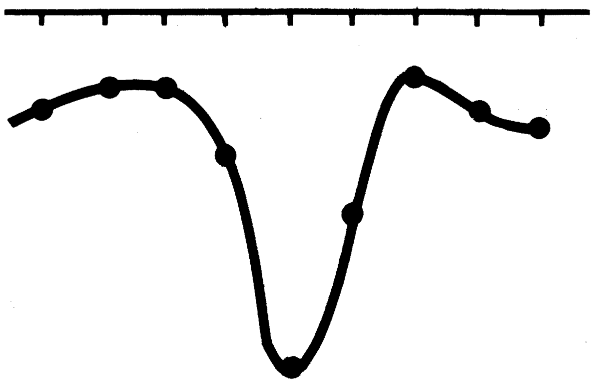
Fourier has some nice properties, for example, it is not dependent on translation, and orientation can be removed. Unfortunately, it tends to mask phenomena which human observers see.

Dr. F. El-Hosseiny, Weyerhaeuser, USA

A few years ago I was trying to measure the radii and diameters of textile fibres and I found that there was an observable change with a change in refractive index of the immersion fluid. The difference was very high particularly when trying to measure small objects. I would like to draw attention to this fact as it might not be well known.

Dr. C. J. Taylor

This problem can be extreme with asbestos fibres which are at the limit of resolution of the optical microscope. We use phase contrast images and so the image looks as shown below.



The question that then arises is whether any one pixel forms part of the fibre image or not. We look at the intensity values of the individual cells and fit a curve through these points. If we know the response function of the microscope then a proper measurement of width can be derived though the arguments are complex.

Dr. B. Jordan

This is a serious problem with phase-contrast work. The transfer function of phase-contrast is asymmetric.

Dr. C. J. Taylor

This is true, I was, of course, just citing one example. The main point is that at high magnification it is important to take account of the microscope optical transfer function during the measurement and analysis phases.

Dr. B. Jordan

One can generalise this by saying that one must be very careful with the optics of the image. It is like the old computer saying "garbage-in:garbage-out". If you have poor quality images or if you are working at the limit of your optics then this has to be attended to: you are quite right.

session 7 discussions

Dr. R.P. Taylor

I believe you are using raster-scan, high-resolution image tubes. For images of fibres where there is a high length to diameter ratio would it be possible to use a non-raster type tube where a spot is made to follow an image under computer control? This may be a more efficient technique.

Dr. B. Jordan

Image dissector camera systems are available on the market which do just as you say: Lamont make one example.

Dr. C. J. Taylor

The problem is one of process speed. Devices which track images can only integrate photons from that one point. A raster system integrates photons for the whole of a frame. The time economics of raster-scan devices is superior to random-access devices.

If image storage were a problem then tracking devices may be used but this is not usually the case.

B. Attwood (Chairman)

This was a very interesting session and it could well provide the basis for an interesting one-or two-day seminar.

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