A COMPARISON OF DIFFERENT METHODS OF PAPER SURFACE SMOOTHNESS EVALUATION

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Smoothness of paper surface is an important property from its printability. A number of techniques are available for characterizing the topographical features of the paper surface. These techniques have led to the development of smoothness testers of various types such as air-leak testers, optical contact testers, surface profilers, and a number of ink and liquid application apparatus to assess the smoothness. While all these methods are intended to serve the same purpose, they differ so greatly in their basic approach that the agreement between them cannot be taken for granted. In the present work, these methods have been applied to characterize the surface of handsheets of mechanical pulps. A comparison of these methods reveals that different methods grade these pulps differently, confirming the multidimensional nature of the surface structure and the fact that no single method is sufficient to describe it completely.

Keywords: Surface smoothness; Compressibility; Printability; Air-leak methods; FOGRA-Kam, Surface profiles; Power spectrum

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INTRODUCTION

Smoothness is one of the most important properties of paper required for its good printability. In the assessment of smoothness, an attempt is made to describe the topography of a three dimensional structure of the hills and valleys on the surface. Since these hills and valleys are of random sizes and shapes, a complete description of the surface topography has always defied any simple approaches to do so. Nevertheless, there are several methods and instruments prevalent to measuring smoothness or roughness (Bradway 1980; Singh et al. 1991), each of these emphasizing a particular aspect of the surface. For example, the air-leak testers measure a kind of mean separation between the paper surface and a reference plane, whereas, the FOGRA-kam instrument measures the fraction of the paper surface that comes in contact with the flat bottom of a glass prism. These techniques work very well in cases where the differences in the topography of the surfaces are large. A difficulty arises in the evaluation of the surfaces of papers having very close differences in their smoothness. The air-leak and the optical methods lack accuracy in such cases and, quite often, the measurements do not relate to the printing performance of the papers. In such cases, it is necessary to obtain more detailed information about those features of the surface structure that are related to the behavior of paper in a printing process.

It is supposed that the evaluation of paper surface smoothness should be more relevant from the printability viewpoint if it is based on a method in which the paper is actually printed under conditions similar to those encountered in real printing. A number of such studies have been reported in the literature. For offset lithographic and letterpress processes, a method based on test printing of paper under conditions such that only a partially covered print results, and analyzing the prints thus obtained by an image analyzer, has been suggested (O'Neill 1959; Singh 1990; Singh et al. 1996). Similarly, an assessment of gravure printing smoothness is made in terms of missing dots in a test print (George et al. 1975; Bristow 1980; Pheney 1981; Heintze 2003; Wanske et al. 2007).

Another technique, which is supposed to provide the most exhaustive description of the surface topography, involves recording of surface profiles and then analyzing these recorded profiles statistically to extract characteristic parameters for the surface.

The available profiling instruments may be divided into two broad classes, mechanical profilers in which a fine point stylus traverses the surface, and optical profilers in which laser beam is used to record the profile without any physical contact between stylus and test surface. Both types of profilers have been used in studies of paper surfaces (Roehr 1955; Kapoor et al. 1978; Kent 1984; Dunfield 1990; Mangin 1990, 1993, Wågberg and Johansson 1993; Lemaster and Beall 1996; Gooding et al. 2001; Chinga et al. 2007; Sung and Keller 2008).

Wågberg and Johansson (1993) compared the optical and mechanical sensing methods, and they considered seven printing papers having a wide range of surface roughness levels; very smooth, cast-coated papers to uncoated grades. They observed that differences in coating structure, fiber composition, etc. could clearly be described by the roughness power spectra with both instruments. The two methods gave different results in details of very fine surface structure. They also emphasized that more information than a single roughness index could be extracted from the primary profile data.

While mechanical profilers have the advantage of recording the geometrical features of a surface directly, there is a risk of the stylus leaving a mark in case of paper surfaces. The marking may, at times, be very significant and can leave the recorded profile useless. Enomae and LePoutre (1995) have shown from visual examination of traces left by the stylus when performing stylus profilometry under scanning electron microscope (SEM) at a magnification of x400, that stylus marking depends on stylus conditions, (radius and load), and on the surface hardness of paper. By careful choice of stylus radius and load conditions for the particular surface, one can ensure that there is no permanent deformation and thus assume that one is recording the "unperturbed" profile, although elastic deformations can still occur.

Wanske et al. (2006, 2007) modified a FOGRA contact area tester by equipping it with a high-precision distance measurement system and connecting to a digital image processing system. They found that measurements by a modified FOGRA optical contact tester were better correlated than air-leak methods with the gravure printability results (missing dots) of eight SC papers tested.

In the present work, four different methods, viz., Parker-Print-Surf roughness, FOGRA contact area, partial coverage printing in an IGT, and surface profilometry using a mechanical stylus have been applied to characterize the surfaces of handsheets of mechanical pulps. A comparison of these methods reveals that different methods grade the smoothness of the handsheets differently. It has been observed that the different methods provide measures of different aspects of surface topography and several of these methods may be required to characterize the surface in a comprehensive manner.

EXPERIMENTAL

Materials

Three different types of softwood (spruce) mechanical pulps, namely, a stone groundwood (SGW), a thermomechanical pulp (TMP), and a chemithermomechanical pulp (CTMP) were used in this study. While the SGW and the TMP were commercial mill samples, the CTMP was prepared in a pilot refiner. The pulps were hot disintegrated at 85°C with a total of 3000 revolutions in a laboratory disintegrator. The pulp samples were analyzed for freeness; the Canadian standard freeness (CSF) values were 82 mL, 94 mL, and 143 mL for CTMP, SGW and TMP respectively.

For each type of pulp, handsheets of 60 g/m^2 were made according to the standard procedure described in SCAN-C 26:76 in a Finnish sheet former of square cross-section, 165 mm x 165 mm. During sheet making the white water was recirculated, and an equilibrium white water composition was established before saving the sheets for further study. The sheets were couched, wet-pressed against gloss plates at 400 kPa, and air-dried at 23 °C and 50 % RH. One-half of the sheets of each type of pulp were calendered in a laboratory calender in a steel-steel nip at linear load of 50 kN/m. The different methods of surface evaluation were used to characterize the glossy side only.

Methods

Parker-Print-Surf measurements

Parker Print-Surf (PPS) roughness of the handsheets was measured with a slightly modified instrument (Bristow 1982). The range of clamping pressure available in a standard instrument is 0.5 to 2 MPa, but the instrument used in this study was modified so that the clamp pressure could be varied and measured over a wider range. A battery of preset values was incorporated with a microcomputer to control the stepwise increase in pressure up to a maximum value of 7 MPa. The PPS roughness values were recorded as a function of clamping pressure between 1 MPa and 7 MPa.

FOGRA contact area measurements

The optical contact area was measured at three pressures, 2.5, 5.0, and 7.5 MPa in the FOGRA-kam instrument. The FOGRA-kam tester, developed at the German Research Association for Printing and Reproduction Techniques (FOGRA), measures the fraction of optical contact between a level reference surface and the paper surface when the two are pressed against each other (Albrecht and Brune 1971).

The bottom surface of a glass prism is illuminated at an angle greater than the angle of total reflection (41°8'). The light is totally reflected by the prism if its bottom surface is in contact with the air. This totally reflected light is measured by a photocell positioned at an angle equal to the angle of the incident light. On the other hand, when a paper surface is in contact with the prism, the incident light enters into the paper and is scattered in all directions. Only a very small portion of the diffusely reflected light reaches the photocell. Thus the light reaching the photocell indicates primarily the regions of non-contact. The ratio of the intensity of the light reaching the photocell to that of the incident light gives the fractional non-contact area.

Partial coverage printing

For each type of handsheets, a series of specimens were printed in a laboratory printability tester (IGT/AIC_2 model) with varying amounts of ink on a polished metal disk. The other printing variables such as speed, printing pressure, and type of ink were kept constant during the printing. The prints were made using the IGT offset ink, at a speed of 1 m/s, with a printing force of 100 N on a 31.5 mm wide strip. A rubber blanket was used for backing the paper during printing. The impression area on the paper was 31.5 mm x 182 mm. Although other conditions could also be selected, but the ones used in this study were found satisfactory. The amount of ink on the printing disk and the amount transferred to the paper were determined by weighing the disk before and after printing.

The prints were evaluated in a Kontron IBAS image analyzer. In this analyzer, the prints were viewed in a TV camera under uniform illumination and the image was converted to a 512 x 512 pixel matrix, each pixel with 256 grey level values ranging from 0 (=black) to 255 (=maximum white) proportional to the local reflectivity times the local illumination. The digital image was stored on magnetic media for further processing in the analyzer's computer. The image width could be adjusted within the 1-50 mm range, and the spatial resolution in the digitized image becomes 1/512 of the width chosen.

The primary scan showed that the print consisted essentially of printed and non-printed areas. The image was, however, normalized, sharpened, and converted to a pure binary image by discriminating at the middle grey tone level, and the fraction of the surface covered by the inked regions was assessed from the count of the black pixels. The test area used was 10.4 mm x 10.4 mm, and the values recorded were the means of three independent measurements.

For image sharpening, grey level transition zones were first detected using a Laplace filter [12]. Within these zones, a moving window checked each pixel to see whether its grey level was closest to the local maximum or minimum grey level in the window at its present position around the checked pixel. This pixel was replaced with either the maximum or the minimum level which was the closest. This led to a sharper transition between the printed and unprinted reflectance values. The subsequent segmentation into a binary image was then less ambiguous with less noisy edges.

To determine the segmentation level, the lightest and darkest 1/1000 area fractions were determined. These levels were considered to correspond to typical unprinted and printed areas and the threshold level between them was then set to the average of the two levels. This procedure gave an inherent stability of the segmentation with respect to factors such as changing illumination, camera response, etc.

For this routine to be accurate, the image should contain at least 1/1000 area fraction each of printed and unprinted regions. In, for example, a completely ink-covered image area, the threshold would be forced to lie within the grey levels of the inked paper and might result in an area fraction in magnitude of 50%, while the true value was 100%.

A similar situation would arise if area fraction were to be measured on unprinted paper. The accuracy of assessment was also checked against patterns of known area and it was confirmed that the image analyzer measurements were fairly accurate for printed area fraction between 0.1 and 0.9.

As an alternative to the image analyzer, the coverage area was also determined from the reflectance measurements of the prints using an Elrepho reflectometer with an FMY/C filter, each print being placed over a pad of the same unprinted paper. Average values were obtained for three independent measurements on a circular field with a diameter of 30 mm. For computing the fractional coverage area of test prints, it was assumed that the reflectance factor of partially printed surface was the mean value of the reflectance factor of the full-tone print and of the unprinted paper weighted in proportion to the areas of the printed and unprinted regions, according to the expression,

$$R = A\,R_p + (1\text{-}A)\,R_\infty \qquad \text{or} \qquad A = (R_\infty - R)/(R_\infty - R_p) \qquad (1)$$

where R is the reflectance factor of the printed strip, R_∞ is the intrinsic reflectance factor of the paper, R_p is the reflectance of a thick layer of the ink on the paper, and A is the fraction of the paper surface covered by the ink.

The agreement between the two methods of determining fractional coverage was observed to be very good.

Autospectra of surface profiles

The surface profiles of the handsheets were recorded by a 'perthometer' surface profiler consisting of a diamond stylus weighing 80 mg with a spherical tip of 3 μm radius. The stylus was fitted in a small pickup such that it could move freely in the vertical direction, while the pickup rested on the surface. As the pickup along with the stylus was traversed on the surface, the vertical position of the stylus was measured with a positional transducer which generated a voltage proportional to the displacement of the stylus. The output voltage was digitized and converted to actual distance by calibrating the sensitivity of the amplifier against a standard which consisted of a metal plate engraved with a groove of known depth (9.3 μm in the present instrument).

At the time of scanning, the paper specimen was mounted on a smooth metallic table, and the pickup, along with the stylus, was moved over the paper surface with the help of a constant speed motor. The stylus readings were recorded by a computer at fixed intervals of time. The speed of movement of the stylus and the time interval between two consecutive readings corresponded to distance intervals of 4.5 μm. After the complete profile was recorded the data were used for further statistical analysis.

RESULTS

Parker-Print-Surf Measurements

Among the air-leak testers, the Parker Print-Surf (PPS) roughness is considered to provide the best correlation with print quality. The PPS tester allows the roughness of paper to be expressed in geometrical units, uses high clamping pressures in the range of pressures used in commercial printing practices, and uses a narrow metering land to prevent air from flowing through inside the paper or leaking out from the backside. In addition, the modification of the standard PPS tester by Bristow (1982) allowed the measurement of surface compressibility of the paper along with the roughness.

Figure 1 shows the Parker-Print-Surf (PPS) roughness values plotted against the clamping pressure in the PPS instrument for the handsheets of TMP, SGW, and CTMP, both before and after laboratory calendering.

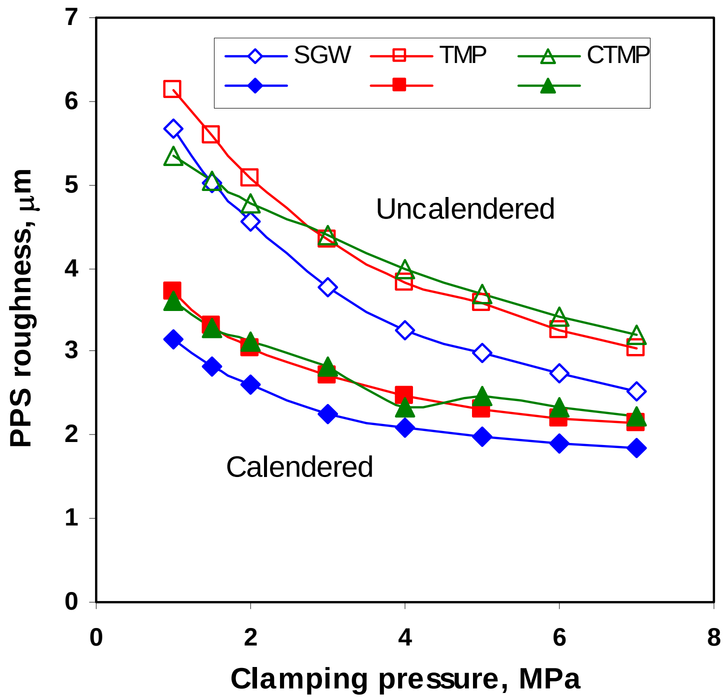

Fig. 1. Parker-Print-Surf roughness as a function of clamping pressure

At a clamping pressure of 1 MPa, the CTMP sheets prior to calendering were slightly smoother than SGW and TMP, but at higher clamping pressure the SGW and TMP sheets were slightly smoother than the CTMP, indicating that the sheets of SGW and TMP had a greater surface compressibility than the CTMP. The PPS values for all the three pulps were, however, very close to each other. After calendering, all the sheets were smoother and less compressible. It is, however, evident that the sheets of SGW pulp became the smoothest with increasing clamping pressure, and that, as a result of its greater surface compressibility, this pulp showed the best response to calendering.

FOGRA Contact Area Measurement

Figure 2 shows the FOGRA-kam values as a function of pressure for SGW, TMP and CTMP pulps. It is interesting to note that the SGW sheets were shown to be the roughest by the FOGRA-kam method, whereas they were found to be the smoothest by the PPS method. The TMP has been found to be the smoothest of the three pulps with regard to contact fraction, whereas it had the highest PPS roughness value at least at lower pressures. A similar trend was observed with the calendered sheets.

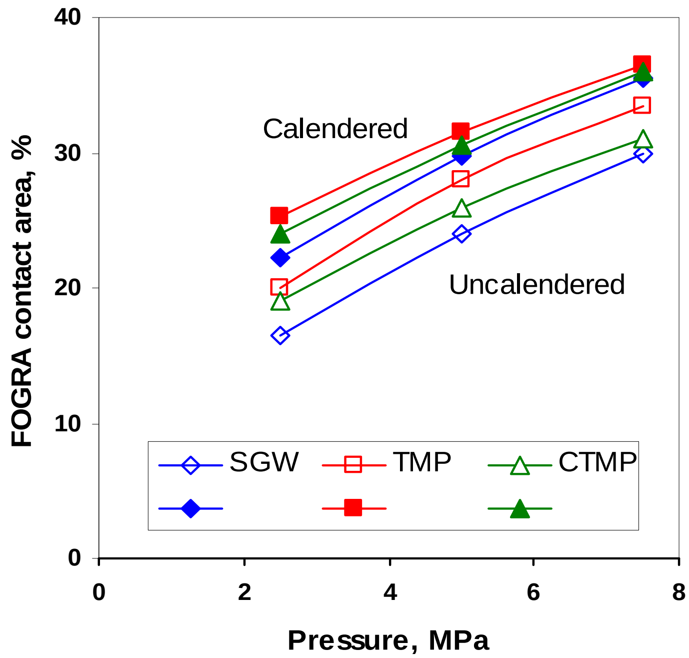

Fig. 2. The FOGRA contact area as a function of pressure for the handsheets of SGW, TMP, and CTMP pulps

Partial Coverage Printing

In the partial-coverage printing technique (Singh et al. 1996), the paper to be studied is printed with a small quantity of ink under a light pressure in order to provide a print with only partial coverage. The prints, thus obtained, present the surface structure in a manner suitable for useful visual examination, as well as for quantitative evaluation. The advantage of this method is that it characterizes the surface in terms of several parameters that are different measures of the surface features and describes the surface structure much more exhaustively than any of the methods which give only a single quantity for the total surface structure.

If a surface is printed under fixed printing conditions, the degree of coverage of the surface will depend on the degree of contact between paper and the ink layer on the printing plate and will provide a measure of the surface roughness. Under any specified set of printing conditions (speed, nip pressure, type of ink etc.), the fractional coverage of the paper surface, A, depends on the amount of ink on the printing plate, x. This relationship between A and x provides useful surface parameters.

The value of x at A = 0.5 represents the depth and the value of dA/dx at A=0.5 represents the slope of the cavities in the paper surface. The value of the square root of the product of x and $1/(dA/dx)$, both evaluated at A = 0.5, is a combined measure of the surface roughness. From a study on a number of different grades of paper, Singh et al. (1996) found that this value was approximately equal to the PPS roughness measured at clamping pressure of 1 MPa, and they designated it by the *Z*-parameter. The values of x at 50% coverage, (dA/dx) at 50% coverage, and *Z*-parameter for the three pulps are shown in Table 1.

Table 1. Surface Characteristics of the Handsheets (60 g/m^2) Evaluated by the Partial Coverage Printing Method

Surface Parameter	Uncalendered			Calendered		
	CTMP	SGW	TMP	CTMP	SGW	TMP
x at 50% coverage	2.12	1.44	1.75	1.87	1.23	1.56
(*dA/dx*) at 50% coverage	0.29	0.38	0.29	0.31	0..43	0..32
Z	2.70	1.95	2.46	2.46	1.69	2.21

The amount of ink required for 50% coverage was least for SGW and most for the CTMP. These values suggest that SGW had the best printing surface among these handsheets, with TMP in second place and CTMP third. The method rated the three types of handsheets in the same order even after calendering.

The printing experiments were conducted at a printing force of 100 N with a 31.5 mm wide printing disk. The choice was guided by the desire to achieve a reproducible partially covered print so that maximum qualitative/quantitative information about the surface topography could be extracted. It may be noted that the printing pressure selected is apparently less than the pressures used in PPS and FOGRA-kam methods.

Autospectra of Surface Profiles

There is a sustained interest in the method of surface evaluation based on profiling instruments, since they provide the most exhaustive description of the surface structure.

A perspective view of the surface structure can be obtained by plotting a number of profiles together (Climpson 1984; Kent 1984). Any defects in the paper surface are clearly visible in these plots, but this technique is very time consuming, the area examined is small, and it yields no quantitative information. A number of approaches have been reported in literature where such profiles have been statistically analyzed to yield quantitative roughness parameters (Roehr 1955; Kapoor et al. 1978; Aschan 1986). In the present work autospectra of surface profiles were calculated to represent the characteristic features of a surface. The typical surface profiles of the three types of handsheets are shown in Fig. 3.

The profiles of a paper surface are stochastic in nature. The characteristics of such data can be described by their average statistical parameters. A number of statistical approaches have been reported in the literature to calculate mean depth and width of surface cavities, but details of great significance are lost in various average quantities. In an approach similar to the one used by Norman and Wahren (1972) for characterizing the formation uniformity of paper, the autospectrum (or power spectrum) of the surface profile is used to present the important features of the surface topography in a simple manner. The autospectrum is a Fourier transform of the autocovariance function of the profile, and it presents the distribution of the variance in the profile data at different frequencies. The total variance of the profile data is given by,

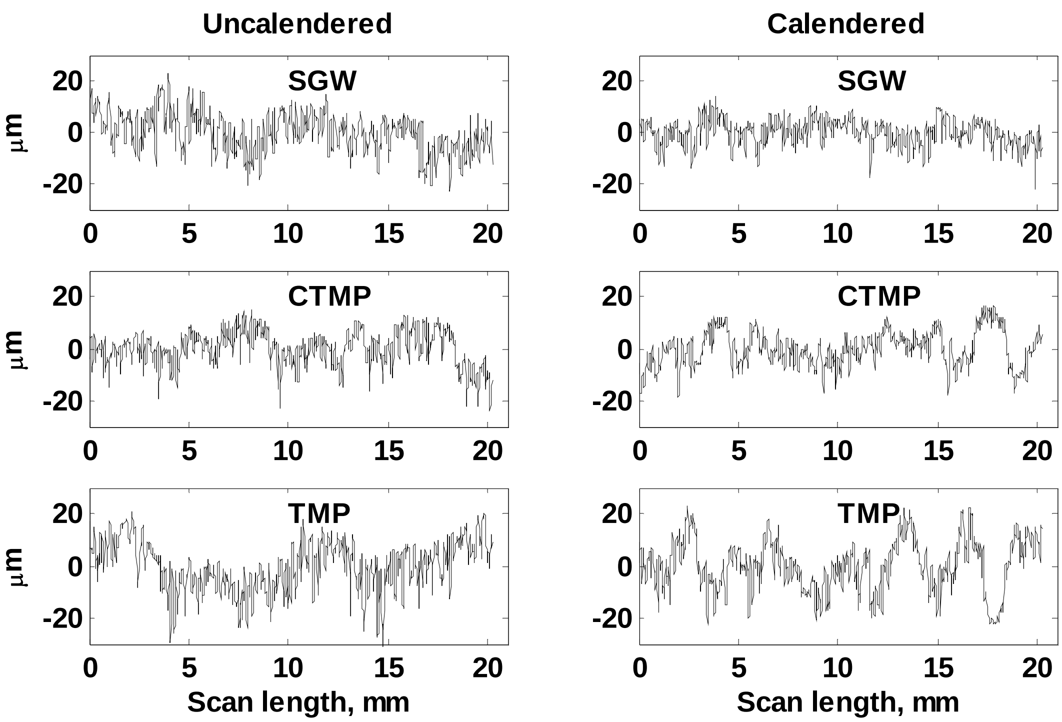

Fig. 3. Surface profiles of uncalendered and calendered hand sheets of SGW, TMP, and CTMP pulps

$$\sigma^2 = \int_0^\infty P(f)df \tag{2}$$

where $P(f)$ is the power of the data series at frequency f, and σ is the standard deviation of the data from the mean.

The techniques for calculating autospectra are well developed and documented (Jenkins and Watts 1968). The standard software packet MATLAB R2006b was used for these analyses. The estimates of power spectral density of the input signal were determined using Welch's averaged modified periodogram method of spectral estimation (MATLAB 2006).

Although the autospectrum is conventionally calculated as a function of frequency, in the case of a paper surface the wavelength of the profile corresponds directly to the width of the surface cavities and is better related to the physical nature of the surface. The frequency spectrum was, therefore, transformed into a wavelength spectrum, such that the total variance calculated from the two spectra gave the same value as suggested by Norman and Wahren (1972). If $P(\lambda)$ is the spectral power as a function of wavelength λ, then

$$\sigma^2 = \int_0^\infty P(\lambda)d\lambda = \int_0^\infty P(f)df \quad . \tag{3}$$

By setting the above equivalence, $P(\lambda) = f^2\ P(f)$, where λ is the wavelength corresponding to frequency f given by $\lambda = 1/f$.

The autospectra of the surface profiles recorded on the glossy side of the uncalendered handsheets of each pulp are shown in Fig. 4. To interpret these results it is assumed that a surface profile is composed of a number of profiles of different wavelengths and amplitudes superimposed over each other. The variance of the component profiles having wavelengths within a given range is given by the area under the autospectrum over that range. Thus, the autospectrum gives a distribution of the total variance of the profile data in its various wavelength bands. The variance of a random series would be uniformly distributed over the entire frequency range, represented by a straight line of slope -2.

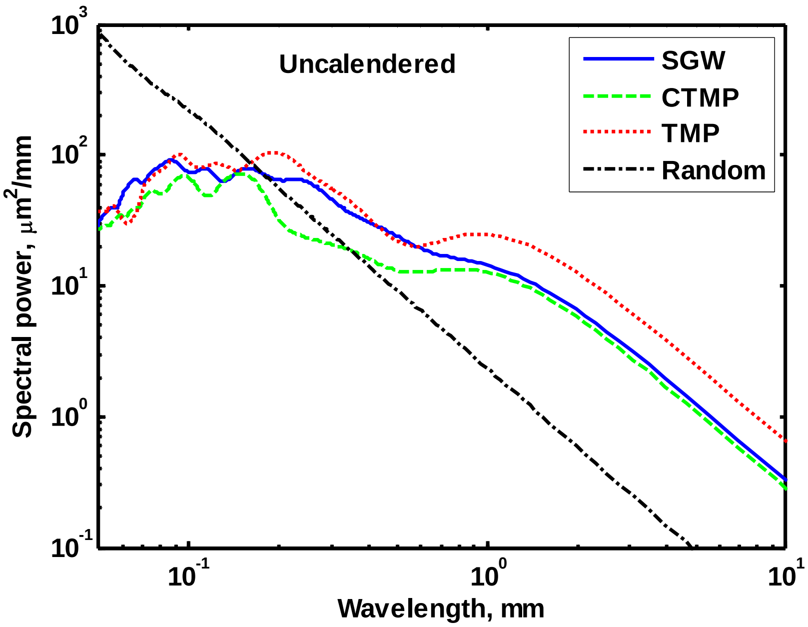

Fig. 4. The autospectra of the surface profiles of the uncalendered handsheets of SGW, TMP, and CTMP pulps

Paper surface profiles differ from a random series in that the contribution to the variance in the lower wavelength region is less than that of a random series and that in the large wavelength region is more than that of a random series. Apparently the paper surface profiles contain random variations with periodic variations superimposed. Some of the predominant wavelengths, which appear as peaks in the autospectrum, must have arisen due to characteristic sizes of the furnish components or to features of specific process steps. The contribution of short wavelengths (< 0.1 mm) is less than that in a random profile presumably because of the finite size of the fibre and other furnish components. On the other hand, the longer wavelength components (>1 mm) are not reproducible, possibly because these variations arise due to waviness of the surface rather than because of the roughness. The distribution of variation in a wavelength band of 0.1 mm to 1 mm is observed to characterize the surface of most grades of paper.

The variance of the sheets of TMP pulp was found to be largest in all of the wavelength ranges, whereas the variance values of CTMP and SGW sheets were very close to each other, with CTMP having a slightly lower value than the SGW. The same order was maintained when the profiles were recorded after calendering the sheets, although the variance in 0.1-1 mm wavelength range was less than that of the uncalendered sheets as shown in Figure 5.

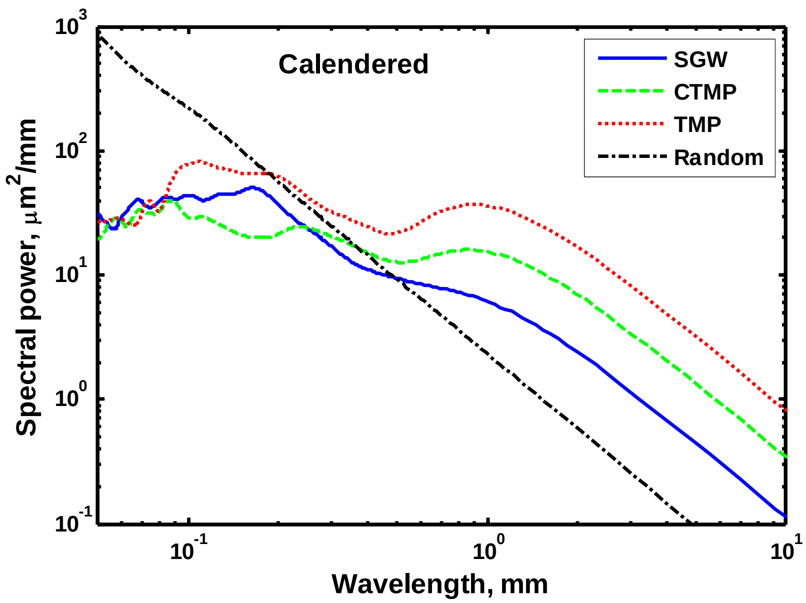

Fig. 5. The autospectra of the surface profiles of the calendered handsheets of SGW, TMP, and CTMP pulps

DISCUSSION

The methods employed for the evaluation of the surface properties of these handsheets rank them differently, as shown in Table 2.

The lack of agreement between PPS and FOGRA-KAM is probably indicative of the fact that the TMP, which shows the better conformability to a flat surface than the other pulps, nevertheless has deeper depressions, which lead to a higher PPS-value. The PPS studies showed that the SGW-sheets had the higher surface compressibility.

Table 2. Smoothness Ranking* of Handsheets by Different Methods

	CTMP	SGW	TMP
Air-leak method (PPS)	2	1	3
Optical contact method (FOGRA-KAM)	2	3	1
Partial coverage printing	3	1	2
Profilometry (Autospectra)	1	2	3

* 1 = Smoothest

The method based on test printing significantly differs from the PPS and FOGRA-kam methods. In both the PPS and the FOGRA-kam procedures, static pressure conditions are used, while printing occurs under dynamic forces. In printing, the paper surface is required to contact a flexible ink film on the printing disk rather than a hard surface such as in PPS and FOGRA-kam. Moreover, the characteristics of the printing ink, the printing pressure, and the printing speed may affect the results.

While the other three methods involve high pressures to compress the sheet during measurement, the stylus method may be assumed to measure topography of a relatively free surface. When the mass of the stylus is considered to be concentrated on a relatively small tip area, it ought to exert quite a high pressure on the surface being measured. From the equations developed by Enomae and LePotte (1995), the maximum and average pressure exerted by the stylus used in the present work (80 mg on a tip of 3 μm radius), are estimated to be 185 MPa and 116 MPa respectively. However, the results of Enomae and LePotre suggest that these pressures are unlikely to leave continuous traces on the surface of uncoated papers.

There has been an interesting observation that while these methods yielded apparently different values of surface smoothness, they all recorded improvements in the smoothness on calendering of the sheets. Except for the PPS tester, where the compression of the sheets was very large, the different methods graded the three pulps in the same order of smoothness before and after calendering.

CONCLUSIONS

This study has been an interesting exercise in the application of various surface characterization techniques to a practical situation when the differences in properties have been small. Different methods rank the handsheets of mechanical pulps differently.

The surface structure of paper is a complex property, and its quantification in a manner that adequately matches the mutual requirements of printer and papermaker is not easy. The results of this study confirm that the numerous methods developed for surface measurement indeed measure different properties. The various tests must always be used with caution and with thought in order to derive the best possible interpretation. There is a need to do more work before the complexity of the relationship between these various tests can be fully explained.

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