OPTISURF – AN NEW OPTICAL METHOD FOR MEASURING SURFACE ROUGHNESS

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ABSTRACT
A new optical method for the measurement of paper roughness is presented. The method provides valuable information about the spatial variation of surface non-uniformity. It can be applied to a wide range of paper types, including specialty papers with laid lines or other imposed structure in the surface of the paper.

The results of studies presented in this paper were performed on various paper types, ranging from photo-quality inkjet paper to sack kraft. The instrument is compared to traditional air-leak methods. The subsequent results demonstrate how the spectral roughness data can be used to benchmark the surface structure of a number of different papers and paper types and how this relates to formation and print quality.

INTRODUCTION
Printability depends on the interaction between paper, ink and the printing process. Good printability typically refers to paper that will produce good print quality for a range of process variables, i.e. it is insensitive to process variations and printing methods. Print quality is a subjective term depending largely on the intended end use of the paper. For example, graphic papers need to be smooth, but the degree of smoothness required depends on the printing method that will be used. Lithographic offset printing, which transfers ink using a rubber blanket, is somewhat less demanding than gravure printing which uses a hard printing form to transfer ink to the paper surface. Similarly, methods used to measure smoothness or roughness may be more applicable to certain products.

Keeping with convention that an instrument that provides a number, which increases with increasing smoothness, measures “smoothness” and one that provides a number that decreases with increasing smoothness measures “roughness”, this technology measures roughness. A number of methods and instruments are available for the measurement of surface roughness or smoothness. Such instruments can be broadly classified as “Air Leak”, “Stylus” or “Optical”. Instruments that rely on air leakage, between the paper sample and a reference plane to determine the unevenness of the paper have been around for over 70 years. They include smoothness testers, Bekk[1] (result reported in seconds, s) and roughness testers, Bendsten[2] (reports air leak in mL/min), Sheffield (reports Sheffield units in cm³/min) and Parker Print Surf[3] (reports m). Traditional air leak methods are fairly quick and robust, but they are indirect and only report a single number to characterize paper roughness or smoothness. Stylus or direct profiling methods, using a mechanical stylus to physically measure the changing surface of the paper. Both stylus and air leak methods are slow and require contact with the paper, they inherently compress the sample and as such are somewhat destructive. Optical methods offer an alternative approach, they are non-contacting, faster and offer the possibility of examining the topography of the paper at a range of scales simultaneously. Various optical techniques have been proposed in the past, including reflection of polarised light, reflection of shallow incidence light and frustrated internal reflection of a glass surface pressed against the paper. Optical methods however have the potential to produce a vast amount of data that needs to be analysed and presented in a manner that relates to the underlying paper structure and the printing process.

The method proposed in this paper is based on the concept of illuminating a paper sample at shallow incidence and analyzing the shadows cast by the surface topography to provide statistical information about surface roughness[4]. The results are presented as indices that correlate well with air leak methods and spectral information that relates to variations at different sizes and as will be shown correlates well with formation.

Scale is important as an average roughness index only provides limited information. For example, figure 1 shows a plot of RMS roughness in m obtained using a stylus device on a lightweight coated (LWC) paper sample. It shows that roughness varies as a function of wavelength or size. This is what one would expect, as roughness at various scales will relate to various aspects of the sheet structure and as such is affected by fines, pigments, individual fibres and formation, each of which will impact a particular scale.
The sample is under slight tension to hold it securely in place against the feed drum. The paper is illuminated over a range of angles from near normal to grazing incidence, by light emitting diodes (LEDs). This creates a pattern on the surface caused by highlighting “hills” and shadowing “valleys”. An image, figure 3, is captured by the digital camera, which is positioned normal to the illuminated surface, the image is then analysed statistically\cite{4}. The sensitivity of the measurement is affected by the location of the measured area of the sample relative to the camera centre line, marked ‘C’ on figure 2. The reflected light is more sensitive to small variations in the surface topography at ‘C’ as the angle of illumination is just above grazing incidence. Consequently the slightest change in surface can cause a significant shadow to be cast (analogous to long shadows being cast at sunset). As the region that is being observed gets further above the centre line, ‘C’, the angle of illumination becomes more normal to the ‘local’ plane of the surface and the shadowing becomes less pronounced (small shadows cast at noon) and the measurements are then less sensitive to the surface topography.

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{image3.png}
\caption{Image of the surface of a sheet of copy paper. Image area is approximately 80mm x 60mm.}
\end{figure}

\section*{DATA ANALYSIS}

The image acquired by the camera is stored as a two-dimensional array of pixel intensities. Along each array, row and column, there is a slowly varying component of intensity caused by the illumination geometry, as well as higher frequency components caused by roughness. The slowly varying component is removed\cite{4,5}. The roughness indices are based on the standard deviation or RMS variation. The RMS variation in intensity is first calculated as

\[ x_{\text{RMS}} = \left[ \frac{1}{N} \sum x_i^2 \right]^{1/2} \]

where \( x_i \) represents the difference between the intensity value of each pixel, \( i \), and the average corrected intensity for a
particular array. The individual array RMS values are weighted and then averaged to give an average “roughness index”. Weighting the data tends to concentrate the measurement to the central region of the image where the variation caused by topographic shadowing is highest. Averaging the row and column indices gives an overall index, referred to as the Optical Roughness Index (ORI). The ORI gives a simple descriptor of paper roughness, which can be compared to roughness measured by traditional air-leak techniques.

However, considerably more information can be obtained by treating the pixel data differently. For example, Fourier transforms give power spectrum information in both row and column (or MD and CD directions). Power spectrum analysis gives information about roughness on different length scales. The instrument offers a field of view of 8cm by 6cm with an optical resolution of 125µm. This resolution allows for example, the isolation of roughness caused by wire-marks; or, permits the study of fine-scale roughness on a sample that has texture embossed on it.

**COMPARISON WITH AIR LEAK MEASUREMENTS**

It is important to ensure that optical techniques, in addition to providing spectral or size data, can also provide roughness indices that correlate to existing air leak methods. Bonham et al[4] showed a non-linear correlation in excess of 90% between the ORI and Parker Print Surf and Bendsten results. This correlation was based on 240 samples ranging from coated photo quality inkjet to sack kraft papers. The Parker Print-Surf and Bendsten methods are industry standards, both based on measuring the rate at which pressurized air leaks under a circular land placed on the paper surface. Both these instruments however have limitations on the smoothness and weight of samples that can be measured, neither of which is a restriction for OpTiSurf. An advantage of the optical technique is that it is easy to use. In addition to roughness indices, Fourier transforms are used to obtain single power spectra in either the vertical or horizontal directions or a two-dimensional power spectrum encompassing both CD and MD directions. The two dimensional FFT of the same samples used by Bonham et al[4] was produced and converted to power spectra. The area under the power spectra was summed over the entire frequency range to produce a total power spectrum intensity for each sample. As such, a higher spectral value relates to rougher paper. Figure 4 shows a plot of the Parker Print Surf and Bendsten results plotted against the total power spectra intensities. It shows an exponential correlation of 85% and 79% respectively with the PPS and the Bendsten.

**Figure 4. Correlation between Parker Print Surf and Bendsten measurements with optical roughness power spectra intensities.**

**COMPARISON WITH FORMATION AND PRINT MEASUREMENTS**

Figure 1 showed a change from 0.3m to 0.7m in roughness over a size range of 0.5mm – 4mm. This demonstrates the importance of measuring roughness for a range of sizes. The range selected from figure 1 relates to the lower range of formation measurement. In order to investigate this further, the samples used to produce the data displayed in figure 4, which range from high quality photographic paper to sack kraft, were assessed in terms of formation using the OpTest Paper PerFect Formation Analyzer (PPF). The PPF[6] uses a two-dimensional FFT approach to decompose formation into ten components of size, ranging from 0.5mm – 60mm. The results of the PPF are compared to “PerFect Paper” which has been mathematically produced and as such provides results that are directly comparable between different samples and different grades. In the case of the PPF, results are on a scale of 1-1000, with 1000 relating to perfect paper, thus a higher value indicates better formation. In this case, the PPF results are based on the average of measurements of 10 different samples, with 6 fields used for each sample. In order to allow a direct comparison between formation and roughness, the optical roughness power spectra measurements have also been decomposed into 10 components sizes, ranging from 250µm to 16mm. The results plotted in figure 5 show the formation and optical roughness results obtained for a range of paper samples. The results represent power spectral results for comparative components, which in this case are defined as C1 (0.5mm- 0.7mm), C2 (0.7mm-1.1mm) and C3 (1.1mm – 1.8mm). PPF power spectra are compared to “PerFect Paper”, so an increase in spectral power relates to better formation and OpTiSurf results measure roughness, so an increase in spectral power relates to an increase in roughness.
Figure 5: Plot of PPF against OpTiSurf spectral results for three components size ranges, C1(0.5mm–0.7mm), C2(0.7mm–1.1mm) and C3(1.1mm–1.8mm).

The results in figure 5 show a general trend that better formation relates to lower roughness. It also shows the correlation between formation and optical roughness at three particular size ranges defined as C1(0.5mm–0.7mm), C2(0.7mm–1.1mm) and C3(1.1mm–1.8mm). The results show that the highest correlation occurs at C1 with an $R^2$ of 0.6956, the next highest at C2 with an $R^2$ of 0.6588 and the third highest at C3 with an $R^2$ of 0.5383. Such spectral data can provide a rich resource for understanding the relationship of roughness at various sizes to process conditions, print quality and subjective assessment. This comparison has been performed on a wide range of samples and gives a general indication that better formation relates to smoother paper. Further investigation will focus on comparing a range of samples from the same grade to determine the relationship between formation and roughness for subtle changes in each parameter and to establish which components have the highest correlation.

Bernie et al[7] has shown that formation of fine paper affects printability at different sizes for different printing processes. The formation components that have the greatest impact on print quality for Harris and Heidelberg presses are 2mm and 5mm respectively. Bernie demonstrated an exponential correlation of 82% for the Heidelberg press with the 5mm formation component and 52% for the Harris press with the 2mm formation component.

The development of this optical roughness instrument, with spectral decomposition related to scale should, allow for a greater understanding between the cause of paper roughness and other properties such as formation and print quality.

CONCLUSION

This paper has presented a new optical method for the measurement of paper roughness. It explains the advantages of optical measurement over air leak methods and demonstrates high correlation between optical roughness indices and air leak methods. This paper also demonstrates the importance of providing spectral information of optical roughness. It explains how this is achieved with OpTiSurf and presents data to explain the correlation of these measurements with other variables that can affect paper quality.

REFERENCES


