OpTiSurf - A New Optical Imaging Method for Measuring Surface Roughness of Tissue, Paper and Board

Roland J. Trepanier, Ph.D.
OpTest Equipment Inc.
Hawkesbury, ON, Canada, K6A 3S3

ABSTRACT

Australian Paper, Amcor R&D and OpTest Equipment Inc. have developed a new optical imaging method that measures the roughness of tissue, paper and board. 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 grades too difficult to measure by traditional air-leak methods such as porous sheets, soft sheets, tissue papers, specialty papers with laid lines or other imposed structure in the surface of the paper.

INTRODUCTION

Print quality is subjective and depends 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.

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 cm\(^3\)/min) and Parker Print Surf\(^{[3]}\) (reports µm). 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 discussed 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\(^{[4,5]}\). Spectral information that relates to variations at different sizes has been shown to correlate well with formation\(^{[5]}\). The spectral size of roughness is important as an average roughness index only provides limited information\(^{[5,6]}\).

TECHNOLOGY

The technology is incorporated in an instrument called OpTiSurf. It is based on the concept of illuminating a paper sample at shallow incidence and using a digital camera to observe the shadows cast by the surface topography. The variation in reflected light intensity is analysed to provide statistical information about surface roughness. The instrument has been designed to accept samples ranging from cut sheets of 80mm wide to a 300mm wide continuous sheet (deckle strip or small reel).

Operation

A sample of paper is fed into the instrument, the sample is held by the nip between the top roller and the feed drum, and by guides around the edge of the feed drum, figure 1.

![Figure 1: Schematic of operation.](image-url)
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 2, is captured by the digital camera, which is positioned normal to the illuminated surface, the image is then analysed statistically\[^{[4]}\]. 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 1. 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.

![Image of the surface of a sheet of linerboard. Image area is approximately 80mm x 60mm.](image)

**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\[^{[4,7]}\]. 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 intensity spectrum information in the sheet feed direction. Depending of the direction of feed either the MD or CMD spectrum is obtained. FFT Intensity 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 LASER PROFILOMETER**

The laser profilometry measurements, on a selection of 8 paper sheets, were made using the calibrated AltiSurf profilometer at Paprican. For each sheet 2 areas were measured on the same side. Each measured area was 64 mm MD X 80 mm CD. Measurements were made at a resolution of 1 µm in both directions with a spacing of 10 µm in the MD and 125 µm in the CD. To measure the 2 areas on a single sheet took at least 12 hours. Paprican applied a 2\(^{nd}\) order polynomial to the remove the large-scale variations from the raw data. The resulting “detrended” data was used to calculate the 1-d RMS (µm), in the MD, for each area tested. The average of the 2 areas was then used to compare with the ORI results, figure 3.

**Figure 3**: Comparison of the ORI (RMS-GL) with a calibrated laser profilometer (RMS-µm)

The 8 sheets were measured on 4 different OpTiSurf instruments and ORI calculated (RMS-
GL). Two measurements per sheet took less than 5 seconds. Figure 3 reveals that the optical roughness reported as ORI and AltiSurf roughness RMS (µm) is significantly correlated to a high level of confidence. This implies that the ORI can be calibrated to RMS (µm).

**COMPARISON WITH AIR LEAK MEASUREMENTS OVER A WIDE RANGE OF PAPER GRADES**

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 spectra are obtained over a size scale from 0.25 mm to 32 mm.

The same paper samples used by Bonham et al\[^4\] were measured on the OpTiSurf and the 2-d FFT power spectra determined. The area under the power spectrum curve was calculated over the entire frequency range to produce a total power spectrum intensity for each sample\[^5\]. As such, a higher 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.

The non-linear relationships between the air-leak roughness and the optical imaging roughness methods are evident if Figure 4. This non-linearity limits the range of different grades that can be measured by each air-leak method and complicates attempts to compare different air-leak technologies.

**APPLICATION ON TISSUE PAPERS**

Sanitary tissue papers cannot be measured using common air-leak roughness methods. These grades are too porous and/or compressible. A 1-ply tissue typically has a grammage below 15 g/m\(^2\) and lacks the stiffness to be fed into the apparatus while being held snugly against the backing cylinder, figure 1. A method was devised where the tissue was mounted on a flexible flat backing sheet with a slight in-plane tension. The mounted tissue and was then inserted into the OpTiSurf for analysis.

**Facial Tissue Softness**

A Canadian tissue manufacturer provided three sets of 2-ply facial tissue. A panel of judges at the manufacturer had ranked these as soft, acceptable and roughest. There is an expectation that surface roughness is one of the attributes that impacts softness.

The sheets were separated in to single plies and the top ply mounted for testing. The MD direction of the tissue was tested as to ensure that the crepe was included in the analysis. Figure 5 reveals that the ORI increased as the panel ranking indicated that sheet was less soft.

The OpTiSurf also provided FFT Intensity Spectra data in the form of 7 optical Roughness Intensity components. These are plotted in figure 6. However, it is the Relative Roughness that is most interesting to study, figure 7.
The intensity of the embossing may vary from the inner layers of the bathroom tissue (BRT) roll, near the core, to the outer layers. Also, the embossing quality may vary from roll to roll, fig 8.

Two sets commercial BRT rolls were provided. Each set contained 4 BRT rolls. One set had acceptable embossing whilst the other did not.

From each roll a sheet was sampled at: 3 layers from the core, ¼” from the core, ¾” from the core and 3 layers from the outer layer. The sheet were mounted and measured both in the MD and CD.

Figure 9 reveals that the ORI, and thus the embossing intensity, diminishes when going from the BRT core to the outer ply. Also the ORI was greater for the acceptable samples (triangle identifiers in figure 9) compared to the unacceptable samples.

Bathroom Tissue Embossing

A bathroom tissue manufacturer required a quantifiable way of determining the variation of embossing intensity. It was anticipated that the relative roughness would serve as a measurable indicator of embossing intensity.
Figure 10: The MD Roughness (embossing) Intensity spectra from 0.25 to 32 mm for BRT samples taken 3 layers from the core.

Figure 11: The CD Roughness (embossing) Intensity spectra from 0.25 to 32 mm for BRT samples taken 3 layers from the core.

Figure 12: The R4 (2-4 mm) Relative Roughness Intensity of BRT samples from 4 roll diameter locations.

The Relative Roughness intensities at size component R4 were calculated at each BRT roll diameter position, figure 12. The Acceptable sample was used as the reference sheet. A value less than 1 indicates that the test sheet has a lower roughness (embossing) intensity relative to the reference sheet.

Figure 12 shows that, on average, the R4 MD relative embossing intensity was about 60% of the acceptable level and that the CD relative embossing intensity was about 45% of the acceptable level. This approach provides a bathroom tissue manufacture with a quantitative method of monitoring embossing intensity.

CONCLUSION

This paper has presented a new optical method for the measurement of paper and tissue roughness. It explains the advantages of optical measurement over air leak methods and demonstrates high correlation of optical roughness indices with laser profilometry 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 affect paper quality.

A wider range of grades may be measured by the optical roughness technique described above. Applications for facial tissue softness and bathroom tissue embossing were given in this paper.

REFERENCES