INSTRUMENTATION DEVELOPMENT FOR THE PULP AND PAPER INDUSTRY

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ABSTRACT

This paper describes several instruments that were developed from first principles for the measurement of several quality issues that affect the marketability of pulp and paper. The present competitive global marketplace places increasing demands of product quality and uniformity. This requires the replacement of traditional human subjective assessment by electronic instruments. The challenge of electronics replacing qualitative evaluations is that the variation in the measured quantities in a production environment is usually quite small, yet the economic consequences profound. The instruments discussed in general terms in this paper use optics, signal processing electronics, image analysis technology to provide useful measurements of paper mass distribution, paper surface topography, surface dirt on pulp, residual ink in paper, that are applied in quality assurance and process control at MacMillan Bloedel.

INTRODUCTION

The measurement of product quality is central to a company that manufactures a product. Manufacturers that produce substandard products or products of a high degree of variability simply do not survive in today's global marketplace. One only need to think how the introduction of Japanese electronics and automobiles have displaced North American manufacturers of these items or have forced them into substantial changes in the way products are manufactured. Quality measurement and control is now a crucial issue for every manufacturer.

Traditionally, many measurements made in the pulp and paper industry are made by visual subjective means. This includes holding paper to a light source to examine the "look through", examining printed images for "mottle" or print quality, assessing the "feel" of paper by touch and so on. It is clearly difficult if not impossible to optimize a papermaking process based on such highly variable and subjective evaluations. Competitiveness is attained only when nebulous quality parameters can be quantified in a reliable fashion. Instruments that provide a manufacturing company a competitive advantage are generally not commercially available for if they were, the leading edge they offer soon diminishes as they become adopted throughout the industry.

Therefore, instrument development for a resource based company is justified on the basis that once a development is successfully implemented in the production environment, the payback in terms of a competitive advantage is gained by having the availability of non-commercial instrumentation. A major obstacle to overcome however, is the gap between what works on a laboratory bench and to have the same device reliably perform 24 hours a day 7 days a week in the mill environment. Mill instruments have to endure the rigours of high humidity, air-borne lint and oil vapour, spraying water and pulp, fluctuations in temperature, line voltage, loss of air pressure, ill treatment from mill workers and neglect from maintenance personnel or instrumentation mechanics unfamiliar or reluctant to service non-standard sensors. Preparing a sensor device for the mill environment is not unlike the same procedure in preparing a satellite to survive the hazards of outer space.

Therefore, the packaging of the on-line instrument is crucial if it is to have any degree of longevity on the production floor. Fail-safe interlocks and mechanisms must be incorporated into the engineering of the device to ensure a reliable operation. Another requirement is to have the instrument self-regulating and auto-calibrating to adjust for changes in the production conditions. With all these stipulations, even the simplest instrument such as a photodiode to detect the reflectivity of paper becomes a serious undertaking requiring an intensive bout of engineering design to circumvent all the difficulties associated with implementation.

This paper will describe the development of both on-line and bench-top versions of a variety of instruments that have found use in addressing quality concerns.

"FORMATION" MEASUREMENT

Paper is made of aggregates of fibers in suspension which agglomerate into structures of varying density referred to "flocs" in the industry. All paper naturally consists of variations in density which can be readily realized by looking at a paper sheet illuminated from behind. The variations in the transmitted light provide an indication of the variation of the basis weight through the well-known Lambert-Beer relation:

$$I(x,y) = I_0 \exp - (\alpha * z_{x,y}) \quad (1)$$

where α is an effective absorption coefficient of paper and $z_{x,y}$ is the local basis weight at point x,y in the plane of the sheet. Unfortunately, for the visible range wavelengths the Lambert-Beer law (1) is only a rough approximation since paper has varying optical properties which affect the absorption coefficient significantly. Paper consists of about 50 % void volume with the scale of the voids being of the

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scale of the wavelength of light and greater. Therefore paper is a strongly scattering medium of light. The component fibers of paper are in themselves clear and is largely through the scattering properties of paper that we can actually see it. By way of example, blue light scatters more than red, so that a blue dyed sheet when viewed backlighted will appear considerably less uniform than a corresponding white sheet. A convenient demonstration of this colour dependence phenomenon can be made using different coloured office copier papers which often come from the same paper machine and stock furnish composition.

Thus, equation 1 is convincingly affected by the shade of the paper. Paper when first made on a paper machine has a comparatively porous structure and low density which makes it initially unsuitable for printing since the surface is too rough and too much ink will be absorbed. To overcome this, the paper density is increased through irreversible compression in a series of rolls under high pressure referred to as a calender stack. Such " densification" causes a lowering of $\propto$ since some of the void volume for scattering is lost. Therefore, the density of paper also affects the formation of paper as judged from the variation of visible light transmission through a sheet.

Other process manufacturing variables affect $\propto$ as well. The amount of fine scale particulate matter of sub-micron dimensions that arise from the mechanical pulping process or the addition of clay or other filler material will usually serve to diffusely scatter light thus masking the mass variations of paper. Generally, the assessment of formation by visible light look-through serves only as a convenient approximation to assess the uniformity of a sheet which translates to a transmitted light variation of only a few percent about the mean.

There have been many attempts at quantifying the variation of visible light transmittance through paper. These have been largely single point scanners that processed the detected transmitted light intensity through signal filters to determine the frequency components of the transmitted light intensity. This remains to this day, the simplest method of measuring the formation of moving paper in production as it requires the least sophistication in technology and so is used in several commercial on-line production sensors.

For static sheet measurements in the test laboratory, it is preferable to have the scanning performed electronically rather than mechanically. A CCD video camera is ideally suited for this purpose. The advent of commercially available image analysis hardware and software in the late 1980's has made this task simpler to implement. In this arrangement, a sample is placed over a light table, the transmitted light is imaged by a CCD video camera whose output is sent to a video digitizer and the variation in the transmitted light is calculated by the microcomputer. The MacMillan Bloedel Research (MBR) embodiment of this concept has an 8.5 x 11 " area illuminated by a bank of fluorescent lamps behind a white Plexiglas screen. Interestingly, it was discovered that fluorescent lamps have a significant time variable output that is influenced by vibration and temperature gradients. The variations are imperceptible to the eye but are of sufficient intensity to mask the small variation in transmitted light through a typical commercial newsprint sheet. Therefore the captured transmitted light image I(x,y) has to be processed through a digital filter to remove the low frequency variations caused by the uncontrollable variations in the fluorescent tube light output:

$$I'(x,y) = I(x,y) \otimes G(\mu,\nu)$$

$$= \sum_{y}^{N-1} \sum_{x}^{N-1} \sum_{\mu-\mu_i}^{\mu+\mu_i} \sum_{\nu-\nu_i}^{\nu+\nu_i} I(x,y)g(\mu,\nu)$$

where the $\otimes$ denotes a matrix *kernel* operation. Essentially what happens is that the image is divided into about 250,000 picture elements or "pixels" each of which contains an eight bit value corresponding to the light intensity ranging from 0 corresponding to black to 255 corresponding to white. The digital filter operation makes a comparison of each pixel at location x,y with its neighbouring pixels in the range specified by the kernel size defined by the indices $\mu \pm \mu_i, \nu \pm \nu_i$. Each pixel intensity is replaced with a value corresponding to some function of its neighbouring pixels. In the case of the digital high pass filter, each pixel intensity is adjusted so that the mean intensity within the moving kernel is the mean intensity of the entire image. Such kernel operation with various different neighbouring pixel comparisons are routinely used to process "grey level" images to enhance features, detect orientation, enhance contrast and so on.

The formation of paper with transmitted light measurement is essentially the measurement of the standard deviation of the transmitted light intensities over an area.[1] The standard deviation of transmitted light intensities for a given incident light intensity will diminish with increasing paper basis weight. The effect of the attenuation of the range of transmitted light intensities with varying basis weight must be compensated in order to measure the standard deviation in keeping with the visual assessment of formation by eye. This can be by done by varying the incident light intensity to maintain the detected mean transmitted light intensity to be constant, or alternatively varying the electronic gain of the detector. We have verified that either varying the detector collecting optics aperture, or the incident light intensity or the electronic gain are all equivalent methods of obtaining the same standard deviation of mean light intensities. The simplest and most convenient method that has been adopted is to employ an auto-iris video lens such that the mean detected transmitted light intensity for any sample is kept constant within the linear range of the CCD video camera. The general arrangement is schematically depicted in Figure 1.

The formation is computed as the standard deviation of the transmitted light intensities for the digitized image thusly:

$$\sigma = 10^{*} \ (1/N)\Sigma\,[(I(x,y) - \langle I \rangle]^2 \quad (3)$$

We found that a multiplier of ten in the calculation for the standard deviation produces a convenient range of values ranging from a low of 30 to 80 for a very mottly now obsolescent newsprint. Note that the extreme in formation range is only about a factor of two. Most measurements of commercial concern focus around the differences between 40 and 45 points. A difference of 5 formation points can be discerned by eye and is considered to be a significant change associated with the paper making process.

Acceptance of the video formation measuring instrument was pending on the correlation of visual assessment of a range of commercial newsprints with numerical results. This was done by experienced users in the Print Lab of MacMillan Bloedel Research. The question arose how to differentiate between samples that have the same standard deviation but still have a different mass distribution.

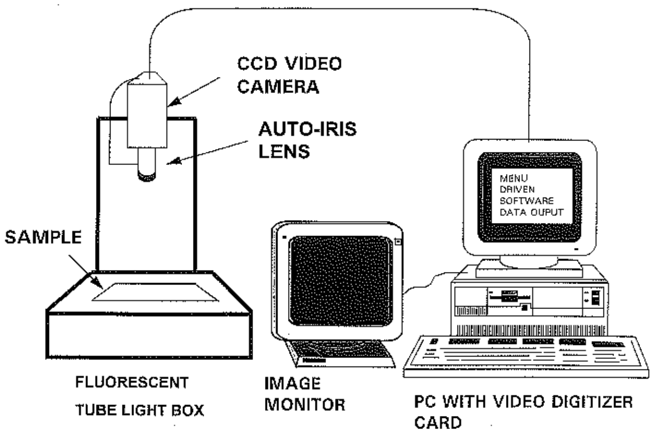

Fig. 1 Schematic diagram of the video based formation tester.

Two samples can have the same mass distribution as measured by the variation of transmitted light but still have a different appearance due to the spatial distribution of the mass, i.e., the samples are said to have differing textures. There have been various attempts over the years to quantify variations in texture using second order statistics and the like. One common method is to segment the dark areas in a transmitted light image of a paper sample on the basis of their lower transmitted mean light intensity. The texture is then the measure of the quantity referred to as the specific perimeter SP defined by the relationship:

$$SP = \Sigma \text{Perimeter} / \Sigma \text{Area} \quad (4)$$

where the perimeter and area refer to those of the dark higher density zones ascribed to some low transmitted light intensity. A low SP indicates a fragmented "grainy" texture, whereas a high SP will characterize a more uniform and even texture.

The variation in SP for most common commercial examples of newsprint is quite small. At MacMillan Bloedel Research we have found that the measurement of the darker high density areas characterized by a mean area size and the area size standard deviation provides a simple means of a second number to describe the paper formation texture.

The measurement of the so-called floc sized distribution is achieved by segmenting the digitized video image on the basis of light intensity. The light intensity at one standard deviation from the mean is selected. This image however, has all the high density opaque zones interconnected. At this point a successive series of "erosion" and "dilation" operations on the "binary" segmented image are performed. This is once again a nearest neighbour pixel operation wherein if a pixel is not surrounded by a sufficient number of pixels that are "on" then that pixel is turned "off" that is, set to zero intensity. The dilation routine will make a comparison of surrounding pixels for each pixel and will turn that pixel on if a sufficient number of surrounding pixels are on. The effect of the erosion operation will divide a binary silhouette image of a peanut into two segments and the dilation routine will tend to fill in gaps or holes in an image. The resulting binary image resembles what the human eye perceives as individual "flocs" in a backlighted sheet as reproduced below:

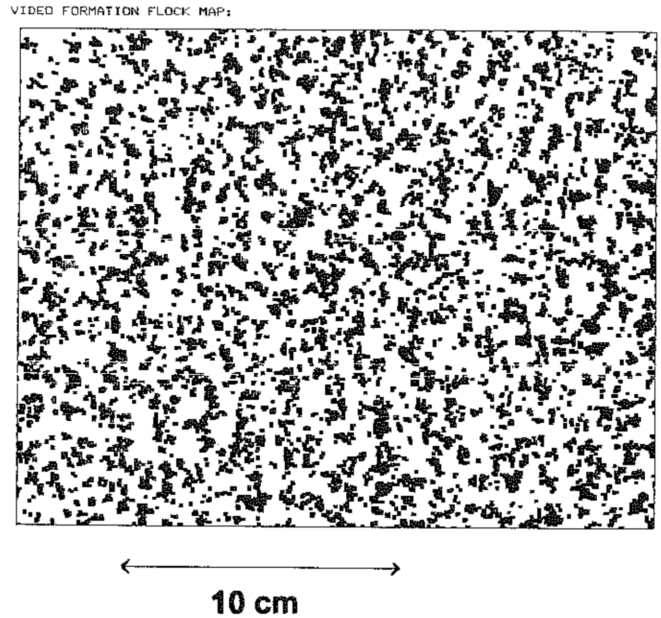

Fig. 2 Binary "floc" map of a transmitted light image of a paper sample. The mean area of these segmented regions provide a second number to characterize the formation of paper.

Once the image has been processed to obtain separated "flocs" the average floc size and standard deviation are computed. Smaller flocs with a smaller standard deviation are considered to be the preferred distributions.

The video paper formation tester has found considerable use in MacMillan Bloedel paper mills in Powell River and Port Alberni since 1989. Its main utility is the quantification of the effects of paper making variables on the mass distribution. An earlier version that does not use the digital filter in the software has been successfully used on heavy weight carton board manufactured at Pine Hill, Alabama.

A variation of the video formation tester that has been provided is for the measurement of the fine scale structure that is superimposed on the paper during the initial drainage of the pulp stock in the paper making process. Paper is made by spraying a jet of diluted pulp stock onto a moving fabric which strains the water leaving a mat of fibers which is then pressed, dried and calendered. Thus, paper making is essentially filtering process wherein fibers in dilute aqueous suspensions are made to conglomerate upon rapid drainage of the water. An impression of the fabric is unfortunately left onto the surface of the sheet which in turn influences the surface roughness and the manner in which paper accepts ink. It is therefore of interest to measure this "wire mark" severity.

A common technique is to employ a two dimensional Fourier analysis of the transmitted light image of paper. Upon close examination of this image one can see the flocs of random size typically of the order of a few millimeters in diameter superimposed upon a regular mesh pattern. This periodic pattern is the "wire mark" and can be readily separated as distinct periodicities in the two dimensional Fourier transform of the transmitted light image of paper. A 2-D Fourier power transform is too computationally intensive for a personal computer to perform on a routine measurement basis. Instead, a filtering technique using the concepts used in analogue formation testers has been adopted.

The "wire mark" intensity in the transmitted light image is known to be in the range of 1.5 mm to 0.2 mm. Therefore, digital filtering of various spatial size is applied to minimize all features that lie outside the wire mark size range. The image is first "blurred" to remove all high frequency artifacts such as pinholes that are smaller in size than 0.2 mm in the image. Blurring is achieved simply by replacing each pixel of the image by the average of its neighbours using a kernel operation as described above. A high pass filter is then applied that obliterates the flocs that are larger than 1.5 mm. What remains then is an image where the mesh pattern in the sheet is enhanced. The "wire mark" value then becomes the standard deviation of this processed image.

This feature to measure the "wire mark" has received the greatest utility in measuring the effect of wire replacement on the paper machine. The drainage wires in the forming section are periodically replaced as a routine maintenance measure. It is the aim of fabric manufacturers to minimize the wire mark impression while optimizing the drainage rate so that this instrument provides a means of quantifying the effects of various fabrics on a paper machine.

ON-LINE VIDEO INSTRUMENTATION

Laboratory quality test equipment is used routinely for product quality control however, it is not optimum for process optimization. This is due to the samples used in the bench tests are taken once every ninety minutes or so thus sampling perhaps only 1/60,000 or less of the paper that has been produced in the interim. Paper is produced at a rate of approximately 1000 meters per minute so that a sampling period of once every 90 minutes is hardly statistically significant given the variability in the nature of the raw materials that make up paper. It is also preferred to have instantaneous quality feedback during a paper machine optimization trial to avoid the convolution of other concurrent changes affecting the results.

Therefore, the video camera technology mentioned previously has been incorporated into on-line versions. Sufficient millimeter scale resolution has to be achieved through stroboscopic imaging of the moving web. Although electronic shuttering of the CCD video camera is possible, this is commonly limited to 1/10,000 of a second which translates to several millimeters in resolution and is unsuitable.

The CCD array is a light intensity integrating device during the blanking period in between its read cycles. Therefore, a short light pulse can be used for stroboscopic imaging when used during the blanking period. In our arrangement, we have used the frame grabbing software to produce a pulse via one of the RS-232 serial port control lines to trigger a General Radio Strobolume 1540. The strobe lamp is placed underneath the sheet and the video camera is overhead. Due to the dusty, warm and humid environment found at the paper machine, air cooling, air purges as well as a pneumatically controlled wiper had to be incorporated to ensure continuous operation of the sensor.

The on-line formation tester operated in much the same fashion as the off-line formation tester. An image of the moving sheet would be grabbed by the combination of synchronized strobe lamp and video camera and the digitized image processed and analyzed for the standard deviation of transmitted light intensities. The basis weight compensation was adjusted by varying the strobe light intensity through a feedback servo-control of the AC power to the strobe lamp. The main utility and advantage of the on-line formation tester is that it produces a continuous stream of data that indicates the degree of variability of the formation of paper. Correlation of the fluctuations of the formation with other process data through a statistical time series analysis allows operators the opportunity to stabilize the paper machine.

A variation of the same CCD camera-strobe lamp technology found considerable use for the detection of surface dirt on pulp sheet. A certain amount of dirt is always present in market kraft pulp due to contaminants such as pitch deposits and the inefficiencies of the chemical kraft digesting process and brown stock washing. Many customers of pulp have stringent criteria in regards to what may be their tolerable level of dirt contamination so much so that pulp mills regularly inspect their pulp sheets for dirt content by manual means employing teams of testers that perform this task. Obviously it is preferable to have an automated objective means to monitor the dirt level content on-line.

Placing the strobe lamp on top of the pulp web, images of the surface of the moving pulp web can be imaged. Dirt specks are detected by segmenting on the basis of contrast intensity. The relationship between the mean light intensity MEAN, the desired segmentation level OFFSET and the intensity for segmentation THRES of the dirt specks was found to be linear:

$$\mathrm{THRES} = 0.9 * \mathrm{MEAN} - \mathrm{OFFSET} \tag{5}$$

The segmentation intensity THRES has to be dynamically recalculated to account for variation in the strobe lamp intensity and the variation in brightness of the pulp sheet. The histogram of pixels versus light intensity spreads out as the mean light intensity increases so that in order to segment the same dark dirt specks it is necessary to decrease segmentation intensity according to the above equation.

Dirt detection by segmentation requires an image with very uniform light intensity. There is always a Gaussian light distribution from lighting and or a lens effect both leading to the edges and corners of the image being slightly but significantly darker than the middle of the image. Video images always have the corners slightly darker than the center. Moreover, uneven surfaces will have shadows that can also been mistaken for dirt when the segmentation method is used for detection. We have minimized these problems by using diffuse lighting in a fashion that is reminiscent of the Ulbricht integrating sphere. The light pulse from the strobe lamp strikes the pulp sheet which then reilluminates a cylindrical tube the inside of which has been sand-blasted and painted white to become an isotropic diffuse reflector. The shadows caused by surface creases are thus eliminated and the image is uniform in intensity much more so than otherwise. The arrangement for dirt detection is shown in Figure 3.

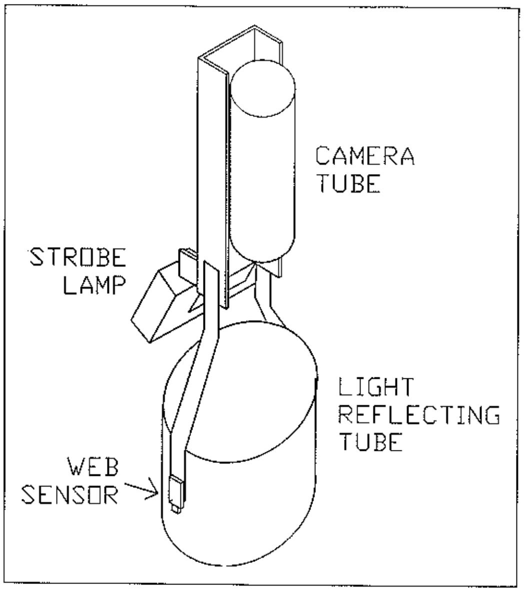

Fig. 3 Schematic representation of the video sensor head used to detect surface dirt specks on moving market kraft pulp.

Use of the video dirt sensor monitor has proven to be useful as a quality control check for human tester data. Marketing judgments have been made which prevented the shipment of off-grade pulp using the results generated by the on-line image analysis system.

ANALOGUE ON-LINE FORMATION TESTER

More recently, we have had greater success with a simpler analogue on-line formation tester. This device essentially consists of an intense variable light source and a photodetector mounted on a "c" - frame through which the sheet passes. A portable commercial unit was obtained for this purpose but unfortunately had to be considerably modified to ensure that it would have adequate sensitivity to detect the small temporal variations in paper formation that occur in commercial production.

The most important modification was the inclusion of an NIR cutoff filter before the photodiode detector. The usual choice of a tungsten filament bulb and Si photodiode detector found in commercial formation testers bias the light response to the NIR. This is unfortunate because paper made from mechanical pulp contains a substantial portion of lignin which is largely transparent to wavelengths 0.7 μm and greater. The interaction of visible light and paper is more rigorously and commonly described by the Kubelka-Munk equation:

$$D = \log (b/a) + aW \tag{6}$$

where D is the optical density defined in terms of the percentage transmission T by $D = \log (1/T)$
and

$$a = (k(k + s))^{1/2} \tag{7}$$

and $b = (k + s)$ where k is the absorption coefficient and s is the scattering coefficient. Therefore, if the scattering and absorption coefficients remain constant, the formation which is the areal variation in optical transmission, is related to the mass density. As can be expected, small particulate matter such as clay fines or chalk fillers scatter more in the blue end of the spectrum. The lignin content in mechanical pulps the absorption coefficient k is 50 times greater in blue region than in the NIR[2]. Therefore, to have sensitivity, a formation tester based on light transmission would preferably have a high blue response.

The comparative transparency of newsprint to NIR light has been utilized in the detection and measurement of residual ink in samples of recycled de-inked pulp in an MBR developed instrument[3]. In this case, the NIR light is able to penetrate the topmost layers of the surface however, the carbon based ink particles embedded in the sheet remain opaque and thus detected by microscopic image analysis.

The video formation testers mentioned previously have a green bias response in the CCD video cameras, thus the correlation with visual assessment has been good. The inclusion of the NIR filter in front of the photodetector in the analogue device also produced a good correlation with visual assessment of paper formation. It is necessary for instrument formation testers to have good correlation with visual assessment for the instruments to have credibility.

Spatial resolution in the analogue device is achieved by imaging the back-lighted paper surface with a lens and placing an aperture at the image plane of the lens. The photodiode-preamplifier combination is placed immediately behind this aperture. The voltage variations are sent through a high pass filter and then through a buffer current driver. The voltage rms values in the range of 300 to 20 kHz are digitized by a voltmeter with a serial port and then logged by a personal computer through appropriate data acquisition software and an RS-232C serial link. The is shown schematically in Figure 4.

The main utility of the on-line formation tester is to measure the variability of the formation. Fourier analysis of the trend plots often shows definite periodicities in the formation variation which may be correlated with the periods of other processes.

MEASUREMENT OF PAPER FORMATION BY RADIOGRAPHY

As mentioned previously all the formation measurements discussed above rely on the transmission of light through paper which is largely influenced by the basis weight of the sheet but also by the optical properties of the paper such as shade, brightness, degree of fiber refining or calendering. This makes the comparison of different grades of paper from different sources difficult and subject to qualification. Attenuation of comparatively energetic radiation such as soft x-rays or low energy electrons is uninfluenced by the optical properties of paper and is only dependent on the paper's basis weight whose variation is of interest to determine. A common technique[4] that is used in several research institutions is a modification of the video formation tester discussed previously where the light throughput through the paper sample is replaced with a film radiograph of the paper.

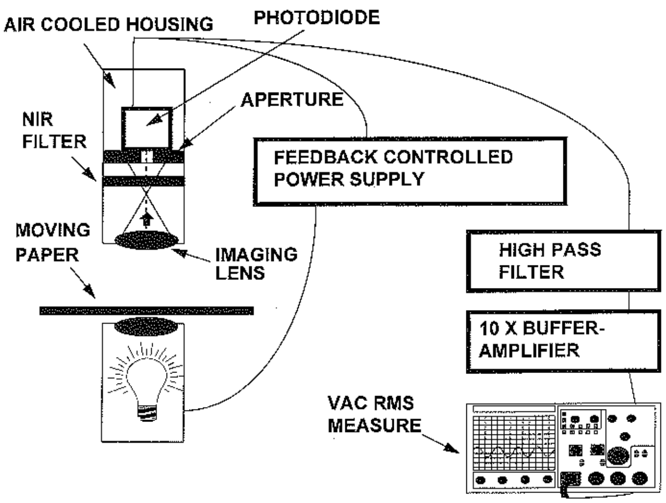

Fig. 4 Schematic drawing of the analogue formation tester used on-line to optimize the paper making process.

The radiograph is made by placing a paper sample in contact with an acrylic plastic sheet impregnated with C^{14} isotope. A step wedge consisting of Mylar layers is exposed simultaneously to the 60 keV electrons from the C^{14} source so that the light transmittance through the various Mylar layers can be used to calibrate the light transmittance intensity in terms of the basis weight. The assumption here is that the attenuation of electrons through Mylar is similar to that through paper since the chemical composition of Mylar is similar to that of paper. The variation of transmitted light intensities through the radiograph are then converted through the calibration to a variation in basis weight which then produces a true standard deviation of the basis weight in absolute units. This is in contrast to the visible light transmission formation measurements which produce only relative numbers.

The use of radiographic film and the long exposure times required make the film radiographic method of formation measurement tedious. The variability in film development and unevenness in the developed film lead to difficulties in going towards quantitative microdensitometry. For these reasons, the preferred method at MBR has been to replace the film with a single point scintillator/photomultiplier detector. The number of detections of electrons per second is recorded directly through an RS-232 port which is also used to activate two linear actuators to provide a snake-like traversing scan of a paper sample placed on top of the radioactive Plexiglas sheet. The scintillator/photomultiplier remains over a position on the sample until 1000 counts are accumulated and is then advanced a few millimeters to the next to scan a rectangular area of paper sample point by point. A simple computer program converts the counts recorded at each point to a corresponding basis weight, processes the array with a moving average filter to remove low frequency variations, and calculates the standard deviation of the basis weight σ which is related to fiber properties by the "universal law of formation"[5] :

$$\sigma = \sqrt{\delta\rho\beta/\omega} \tag{8}$$

where δ is the fiber coarseness, the weight per unit length, ω is the average fiber width, ρ is numerically calculated factor based on geometrical considerations accounts for the measurement resolution and is weakly dependent on the fiber length and coarseness and β is the mean basis weight. The above equation aside from the correcting ρ factor can be derived form dimensional arguments using the fact that fibers are distributed in a random network according to the Poisson distribution. Clearly, the mass distribution in paper is dependent on the average fiber physical properties and the mean basis weight of the sample.

The radiographic scanning method directly measures the standard deviation and is used to correlate the video formation measurements with the basis weight. The general trend is that for most cases of newsprint the correlation between the absolute standard deviation and the measurement of the variation in transmitted light intensity is quite good except in those instances where the green light absorption is markedly different. The utility of the radiographic scanning method is to ensure that small differences in formation are indeed due to mass variation differences and not to optical effects. It has been useful in determining whether differences in printability of competitor samples are attributable to formation differences.

OPTICAL SURFACE TEXTURE SENSOR

An interesting application of some optics principles has been applied in the non-contact measurement of paper surface topography[6]. There is a need to measure the paper surface properties in a non-contact fashion during production to provide informative feedback of the effect of paper finishing processes such as calendering, steam application, or furnish change. The most common method of measuring the surface roughness by measuring the amount of air leakage[7] along the surface using contacting sensing "lands" that are loaded to simulate the pressures encountered in a press nip. Although the correlation of printing properties with the output of such air-leak measurements is quite well established, the sample size is restricted to a minor portion of the total production due to the necessity of clamping a sample for a static measurement.

The reflection from a paper surface is partly specular and partly diffuse. The specular component comes from mirror-like facets of high reflectivity and sufficient levelness to fulfill the specular geometry of the incident angle being equal to the angle of reflection. If perpendicularly polarized light falls on a specularly reflecting surface at Brewster's incident angle θ_b defined by

$$\theta_b = \tan^{-1} n \quad (9)$$

where n is the refractive index of the paper only taken to be that of cellulose at 1.53, then the perpendicular polarization will be preserved upon reflection from the surface. Scattered light will have a random polarization and will be inclined to penetrate into the paper and will be consequently absorbed. In calendered papers, the surface is largely level however higher density zones will be preferentially higher in reflectivity. The geometry of the instrument is shown in Figure 5.

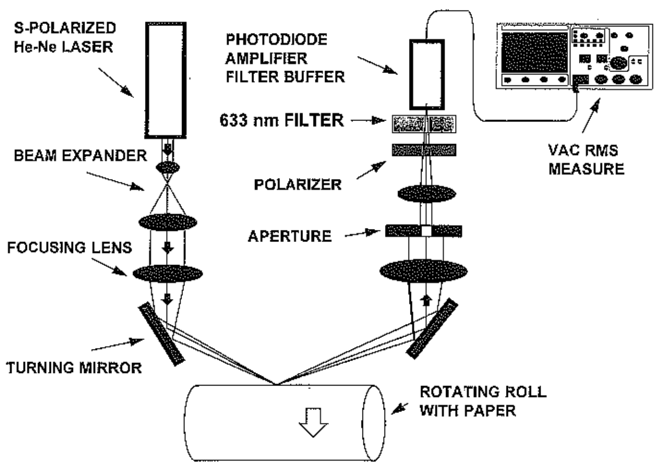

Fig. 5 Geometric layout of the non-contact optical surface topography sensor.

Plane polarized light form a He-Ne laser is sent through a beam expander and a 10 cm focal length lens brings the laser beam to a focal spot to less than 100 μm. Turning mirrors maintain the geometry at Brewster's angle about 57°. The collecting lens collimates the reflected surface light, send the beam through an aperture, polarizer, another focusing lens and onto a photodiode detector. The output signal from the photodiode bias circuit is sent through a high pass filter buffer amplifier and is measured by a true RMS AC voltmeter. The moving paper surface in the focal plane of the instrument creates a time varying signal that contains information about the surface topography.

A smooth paper surface produces a greater time variant signal. This is because the crevasses and voids in the paper surface on the scale of the focal spot remain untouched by paper finishing processes, but the topmost parts of the surface corresponding to fiber bundles and fiber crossings become increasingly better specular reflectors as the surface improves.[i] The way to imagine this is that the paper surface cross section profile may be envisaged much like that of a mesa-canyon landscape. Canyon depths and recesses remain untouched as the paper is compressed into a smoother sheet, but the tops of the mesas become increasingly flattened.

The high pass filter is set such that surface variations of a small scale as determined by the paper velocity are measured by the AC voltmeter. A low impedance buffer amplifier ensures a high frequency response and the capacity to drive long coaxial signal cables. The AC rms amplitude was found to correlate with measurements of smoothness using the Parker Print-Surf air leak instrument as well as with a standard spatially integrated surface gloss measurement.

The optical roughness sensor has found its greatest utility in trial work where an instant feedback was required of the effects of calendering nip load or steam application on the paper surface.

SUMMARY

This article has described the principles involved in the development of several measurement instruments that have been found to be useful for MacMillan Bloedel's quality concerns. These include the measurement of paper formation, surface dirt on pulp sheets and the measurement of surface topography. Basic optics principles are first utilized to test concepts on a laboratory bench. Further arduous development towards a demonstrable prototype instrument requires the practical experience acquired through sound physics laboratory practice to ensure appropriate instrument sensitivity, consistent and reliable performance. As such, instrument development in an industrial research setting can be a rewarding and interesting use of a physicist's training and experience.

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