Off-line Analysis of Properties of Paper Web : A diagnostic Tool to Improve Variability

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SUMMARY

The practicality of accurate off-line measurement of fundamental paper properties such as basis weight, caliper and paper gloss, and the subsequent analysis of such data for diagnosing the source of variability is presented. Case studies reported here showed how this tool has been used in identifying the sources of excessive caliper variation in the machine direction and basis weight variation in the cross and machine directions. Paper formation index or specific formation computed from off-line measured basis weight and light transmission was found to have very good correlation with that measured using Ambertec beta formation tester.

INTRODUCTION

Although variation in paper quality is natural, excessive variation can cause flaws, which in turn cause lost time, rejects and unhappy customers. Over the last decade, the continually increasing demand for improved quality of paper and paperboard has led the papermakers to seek improvement in the uniformity of their products. Minimisation of short to long term variation, in both the machine direction (MD) and cross direction (CD), of the fundamental paper properties such as basis weight, caliper and paper gloss has become a target for all paper producers to improve paper quality and to maximise operating efficiency. The quality of finished paper and hence variability of fundamental paper properties, is influenced by every stage of the papermaking process from the fan pump and screens to the calender. The scale, direction and sources of variability of fundamental paper properties have been well documented by Cutshall (1). The author classified MD variations into four main categories:

1. long term variation (longer than 200 seconds)
2. medium term (200 to 1 seconds)
3. short term (1second to 100 mm wavelength)
4. very short term, micro-level or formation type (less than 100 mm wavelength)

Accurate measurement of fundamental paper properties in both CD and MD is extremely important in identifying the sources of variation. Most modern paper machines are equipped with on-line sensors (or scanner) to measure basis weight, grammage and other properties. However, such measurements are often too slow and scanning across the deckle length does not always provide a true picture of cross and machine direction profiles to allow adequate control.

Very accurate high-resolution measurement of fundamental paper properties is extremely important in order to identify the sources of unacceptably high variation and for subsequent corrective action. Off-line measurement of paper sample could be very accurate and multiple paper properties can be measured at the same time.

A detailed description of an off-line analysis system that has been successfully used for benchmarking of product quality, diagnosis of source of variations and troubleshooting is presented in this paper. Several case studies have also been presented, highlighting the usefulness of such a system.

OFF-LINE MEASUREMENT OF PAPER VARIABILITY

Off-line measurement and analysis of basis weight variation in order to evaluate the of paper machine stock system has been reported in many early publications (2,3). Most recently, Mardon (4) was a passionate advocate of off-line analysis of basis weight as an important tool for paper machine optimisation. In the past, off-line analysis was relatively slow and confined to basis weight and caliper. With the advent of very powerful personal computers and sophisticated sensors, it is now possible to measure several paper properties simultaneously. This fast and accurate measurement, along with suites of software, can provide a powerful tool to the papermaker to improve paper uniformity.

Original system

Since early 1980, Amcor Research and Technology had an off-line system (Atomat) to measure grammage of full-length deckle strips and MD paper rolls of up to four minutes production length. A β-ray gauge (Kr-85 source) was used on the system. Later on, a caliper gauge was added to measure grammage and thickness simultaneously. Data acquisition and analysis software was developed in-house (5). Following expansion of the company's papermaking activities to fine paper grades in the early 1990s, it was deemed desirable to upgrade this system to measure other paper properties such as paper gloss and ash or filler contents.

Current system

In 1994, a commercial off-line paper analyser system, Tapio Paper Variability Analyser (PVA), was obtained. Details of this unit are available elsewhere (6). This unit has been extensively used for off-line analysis of paper grades ranging from 37 gsm bleached bag kraft to 280 gsm linerboard products.

Sensors

Originally, the Tapio PVA had a Promethium 147 (Pm-147) radioactive source to measure basis weight up to 90 gsm. An ash sensor and another basis weight sensor were added in 1998 to measure grammage exceeding 100 gsm. The following sensors are currently mounted on the Tapio PVA :

- **Basis weight** with 5 mm diameter aperture using Pm-147 and Kr-85 radioactive source.
- **Caliper**, with a 0.3 mm contact area
- **Gloss**, top and bottom with 4 x 4 mm aperture
- **Transmission** (inverted opacity) with 1mm aperture
- **Remission** (blackness level), with 0.3 mm aperture
- **Ash** using a Fe-55 source with 5 mm and 10 mm aperture size.

Measurement methodology

For meaningful benchmarking and comparison between various machines and product grades, it is important to adopt a standard methodology for off-line measurement of fundamental paper properties. These include:

- **sample step.** For both CD and MD analysis, 1.6 mm sample step is used.
- **number of full length deckle strips**. Between 25 to 30 strips are normally used, depending upon the grammage. With heavier grade products, the sample cutter restricts the number of deckle strips.
- **inclusion/exclusion of edges for CD analysis**. Both edges are excluded (100 mm from either side) when CD spectral analysis is carried out.
- **length of MD reel.** Total length analysed is generally equivalent to four minutes machine time, although this is restricted by the clearance of the drive spindle and the sensor location of the Tapio profiler.
- **number of MD rolls and locations of such rolls in deckle position.** Generally three MD reels from the same parent roll, cut from front centre, centre and back centre are analysed. Roll location is important as the magnitude of variation may not be properly identified if the roll location in the deckle position is not appropriate.
- **calibration of sensors**. All the sensors mounted on the profiler are calibrated using traceable standards. Calibration of the ash sensor requires information on the composition of ash or filler being used ie, percentage of clay, calcium carbonate, titanium dioxide etc.

Effect of sample step

The exact size of the sample step for paper being analysed using an off-line analyser is very important in terms of the level of variability that is calculated from the measured data. This is also true for on-line measurement. For direct comparison of variability of different product grades made on the same machine or similar grammage products made on different machines, the sample step must be specified. This is particularly true for a new machine or an existing machine with upgraded/new headbox to conform with the vendor's warranty of grammage variability in both cross and machine direction. The grammage and caliper variability in the cross direction was analysed off-line using 30 full length deckle strips at various sample step lengths ranging from 0.8 mm to 124 mm. The coefficients of variation in basis weight and caliper are shown in Figures 1 and 2 respectively.

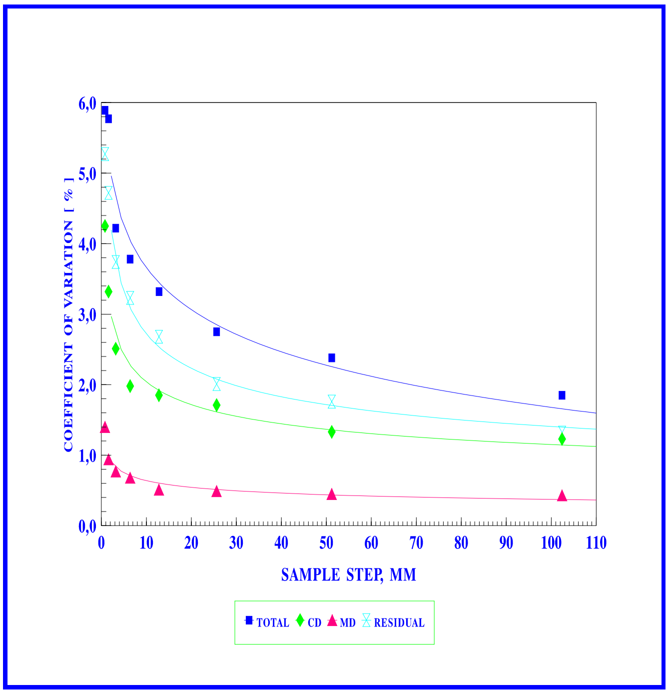

Fig. 1 Effect of sample step on basis weight variability

It is obvious from these figures that basis weight coefficient of variation (total, CD and residual components) are very sensitive to sample step up to 25.6 mm. At higher sample step, the effect is marginal. The caliper variability in the cross direction is also similarly influenced, although to a lesser degree. Graber and Gottsching (7) also showed that standard deviation in grammage is influenced by sample step. Consequently, for benchmarking of grammage variability and evaluation of the performance of a new/upgraded flowbox, it is paramount that a consistent sample step be used.

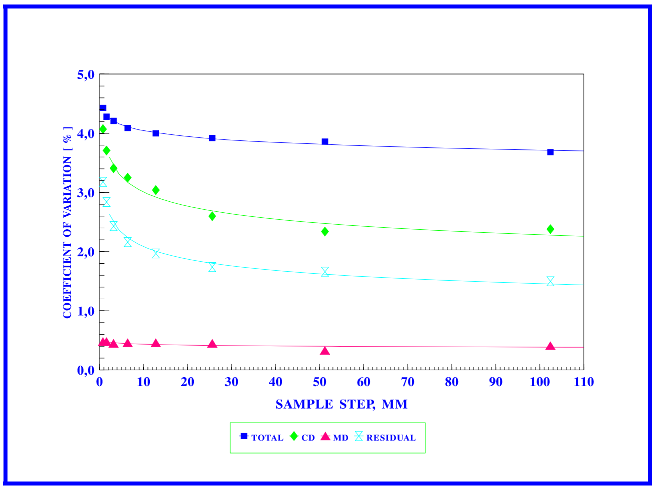

Fig. 2 Effect of sample step on caliper variability

USEFULNESS OF OFF-LINE MEASUREMENT AND ANALYSIS

Off-line measurement of multiple properties of a paper sample in both cross (full deckle strip) and machine direction (MD reel) using a sample step of 1.6 mm can generate a large number of data points. Proper analysis of such data can produce very useful information in terms of potentially better control of both CD and MD uniformity and ultimate improvement in product quality and operational efficiency.

Diagnostics of MD variation

Another significant application for off-line measurement of fundamental paper properties is the diagnosis of the causes of variability in MD. Excessive variation in the machine direction can have a strong influence on variability in the cross machine direction, as de-coupling of CD and MD components from total CMD variation is often difficult. Although ‘true’ MD variation in basis weight and caliper can be measured using the on-machine scanner by ‘parking’ the scanning ‘head’ at any location across the deckle width, resolution of the measured data is low and high frequency variation is difficult to detect.

Frequency analysis of off-line measured data from a paper reel (MD variation) can establish the frequencies at which variation in fundamental paper properties is occurring. This in turn can establish whether the source of the variation is on the paper machine or in the stock approach system. MD variation could be either due to rotational or non-rotational elements. Rotational disturbances could be roll related due to machine components such as

- breast roll
- couch roll
- press/size press rolls
- coating applicator rolls, and
- calender rolls

Non-roll elements can also cause rotational disturbances. Some examples of such elements are:

- fan pump (BW)
- pump for primary screen (BW)
- primary screen (BW)
- wire length (wire mark, BW, caliper, gloss)
- felt length (gloss)

If the frequencies of variation identified from the spectral analysis of off-line measured MD data could not be matched with the rotational frequencies of the major rolls or non-roll elements of the machine and the stock approach system, the following items need to be checked:

- pressure variation at the flowbox
- consistency variation
- vibration around and at the flowbox and wire section

Quantification of ‘true’ CD variability & better control

Analysis of variance of CD basis weight data generated from deckle strip analysis can give ‘true’ CD profiles and coefficient of variation. The presence of ‘streaks’ in the final product that quite often can not be identified from on-line scanner data can be detected in off-line measured data. Another important application of such analysis is verification of the CD actuator system, including isolation of periodic and non-periodic variation in the cross direction. Frequency analysis of CD data can identify control problem(s) arising from incorrect actuator mapping. One such example is shown in the case study.

Verification of scanning systems

Calibration and accuracy of the on-line scanner system is important in assessing the quality of the final products. Off-line analysis can be very useful in the verification of a scanner system. Figure 3 shows such an instance. The caliper measured on-line did not show any significant variability of the finished product. However, when measured off-line using the Tapio profiler, the mean caliper profile in the cross direction was completely different. It not only shows the presence of ridges, but also the absolute values were higher than the on-line measured values. The mill was advised the problem of the on-line scanner calibration.

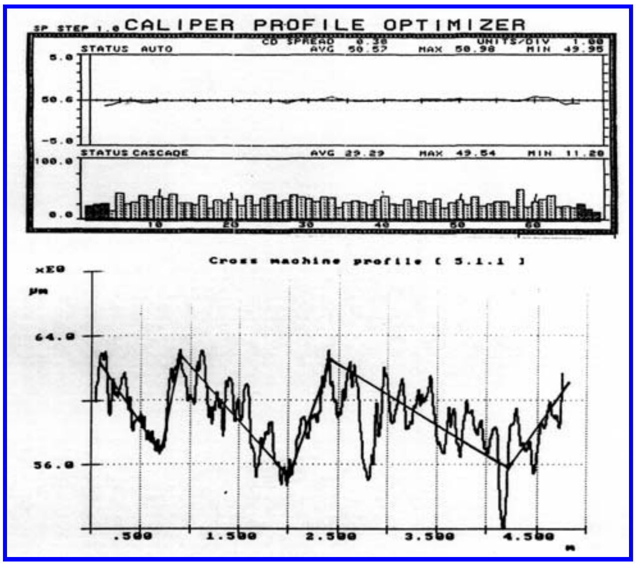

Fig. 3 Comparison of on-machine and off-line measured CD caliper profile (Top graph : on-line; Bottom : Tapio)

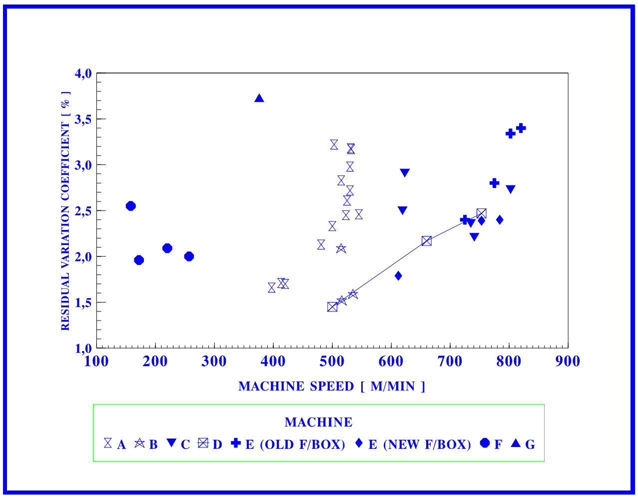

Fig. 4 Comparison of BW residual coefficient of variation in cross machine direction

Benchmarking

Analysis of off-line measured data can be useful to benchmark basis weight variability of similar grades of paper made on different machines. Different DCS systems are generally used in each paper machine with different CD control algorithm. Due to different levels of databox used for each DCS, direct comparison of variability is often meaningless. As shown earlier, sample step greatly influence the magnitude of the basis weight coefficient of variation, particularly the random or residual component of cross machine direction (CMD) variability.

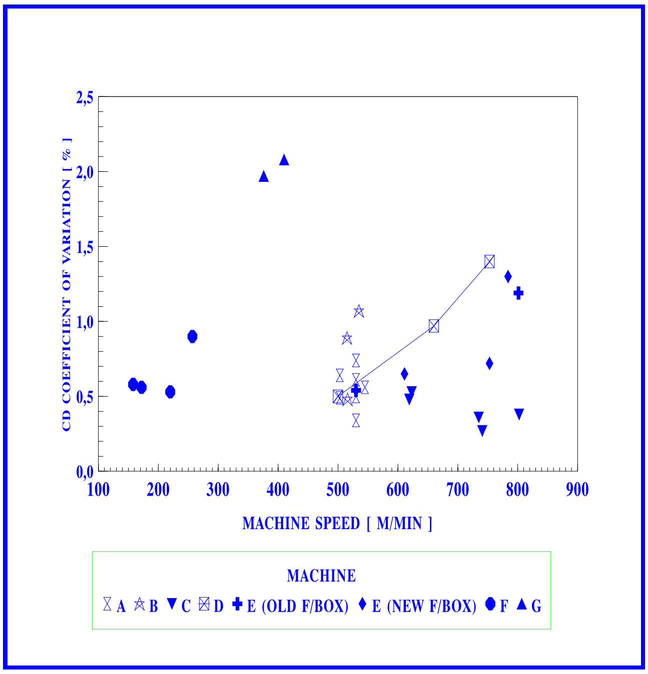

Fig. 5 Comparison of BW CD coefficient of variation in cross machine direction

Figures 4 and 5 show the comparison of basis weight residual and CD coefficients of variation in CMD of similar grades of paper made on different machines as function of machine speed. For machine D, products of the same basis weight were made on the same paper machine at three different machine speeds, and this is shown by the line joining the data points. As expected, both residual and CD components of the basis weight coefficient of variation in CMD increased with machine speed. For machine A, the random coefficient of variation is much higher than all other machines, except F and G, when compared at similar machine speed, suggesting unstable conditions of the flowbox of this machine. The CD component of the coefficient of variation of this machine is relatively low, indicating basis weight profile control in CMD is good and total variability in the cross direction can not be further improved without modification to the flowbox or forming section. For products made on machine G, both the CD and residual components are very high. This suggests that for this machine, not only is the hydrodynamic stability of the flowbox poor, but also the CD profile control is very bad.

Performance evaluation of a new machine or flowbox

Off-line analysis of basis weight can be useful in performance evaluation of paper made on a new paper machine or on a paper machine with a new flowbox. All three main paper machine manufacturers (Voith, Valmet and Beloit) use the Tapio off-line profiler for performance evaluation of paper made on their new machine (8). Mardon (4) advocated that before making a final decision on purchasing a new paper machine or a new flowbox for an existing paper machine, the papermaker need to consider off-line analysis of 20-30 deckle strips of paper made on a vendor's machine and seek similar warranty for the proposed new machine. In Figure 4, the residual coefficients of basis weight variation of same grammage product made on machine E, with the old and new flowbox are shown. Significant improvement in random variability in basis weight is obvious.

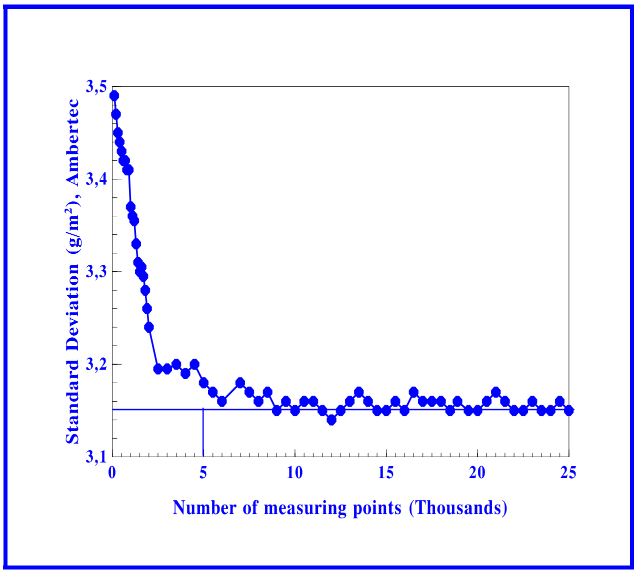

Fig. 6 Effect of number of measuring points on standard deviation.

Measurement of paper formation

Paper formation can be measured by optical transmission or β-ray transmission (micro-scale grammage variation). The Ambertec is one such commercially available unit that is most commonly used industry-wide for off-line formation measurement. This instrument uses a very weak β-ray transmission source (Pm-147, 5 mCi activity). Although this instrument gives more accurate measurement, it is very slow and depending upon the basis weight and the trim width of machine on which paper is made, it may take several hours or days to measure formation for a full length deckle strip (9). The off-line Tapio analyser can be used for fast measurement of formation along with other fundamental paper properties. The analyser uses the same Pm-147 β-ray source, with much stronger activity (500 mCi), and is many times faster than the Ambertec. The drawbacks for use of the Tapio profiler to measure formation are a bigger aperture size (2 mm compared with 1mm for Ambertec) and measurement along a single line, rather than an area. However, when formation is described as standard deviation, only the number of points measured matters, as shown in Figure 6. For measurement of formation using the Ambertec, at least 4900 points (70mm x 70 mm area) are required, which is 5 – 10 times less than the Tapio. Consequently, formation values measured using both systems are expected to correlate.

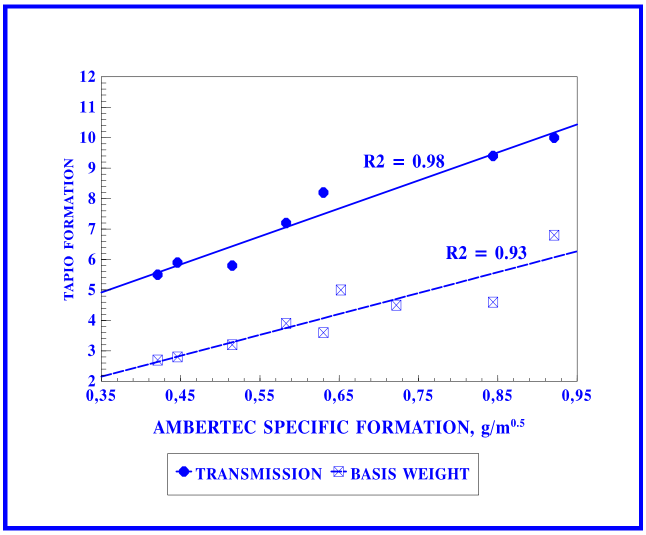

Fig. 7 Correlation between Ambertec and Tapio Formation Index

Formation index measured by the Tapio profiler (defined on a scale between 1 and 10, lower number represents better formation) can be obtained from both measured light transmission and basis weight data. Figure 7 shows the correlation with Ambertec specific formation (defined as standard deviation divided by the square root of basis weight). A very good correlation (R^2 = 0.93 to 0.98) can be seen between formation values obtained from the Ambertec and the Tapio off-line profiler.

Correlation between two paper properties

Accurate off-line measurement of paper properties and subsequent correlation of two properties measured at the same point can provide useful information on the source of variability of one property. As an example, Figure 8 shows the superimposition of basis weight and caliper profiles in the cross machine direction over full-length deckles obtained from a paper machine. The correlation between these properties in this instance is close to 60%. Except over 0.5 m length at the back edge, the shape of the caliper profile exactly matches the basis weight profile, indicating that high caliper variability is due to that of basis weight. The caliper profile could not be improved without solving the problem(s) associated with the CD basis weight profile control on this machine.

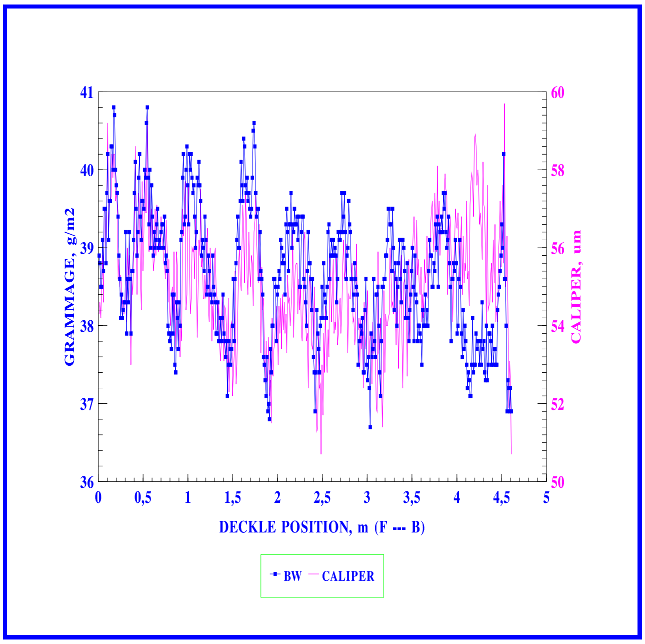

Figure 8 Superimposition of BW and caliper profiles

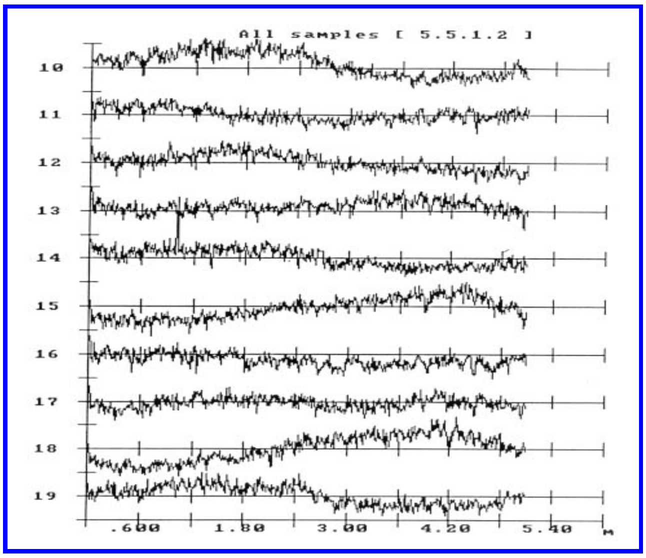

Fig. 9 S-shaped caliper profiles for consecutive deckles.

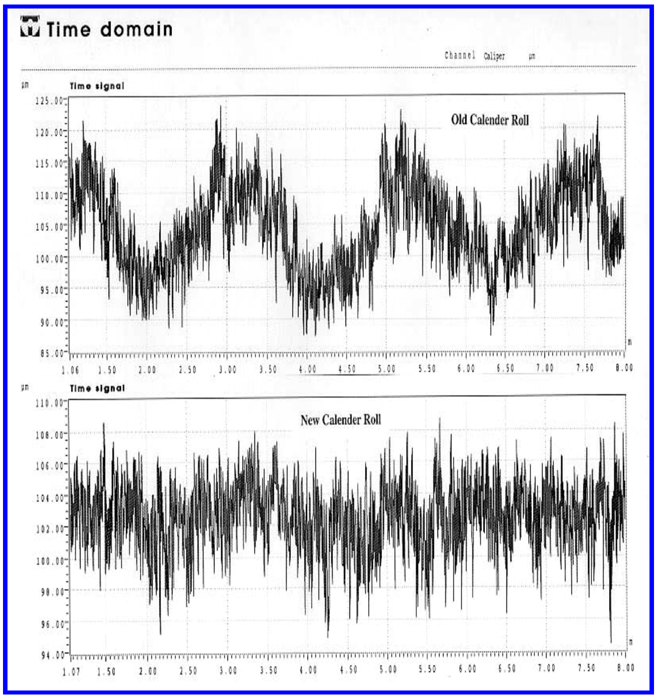

Figure 10 Caliper profile in machine direction with old and new calender rolls

RESULTS: CASE STUDIES

Measurement of fundamental paper properties using an off-line system such as the Tapio profiler and subsequent variability analysis of the measured data has been successfully used by mills in troubleshooting and improvement of product quality. Results of three specific case studies are presented to demonstrate the usefulness of such a system when it is located centrally at R & D centre that serves all the paper mills of the company.

Case 1 : MD Caliper problem

In this example, the product made on machine X was experiencing excessive MD caliper variation. Although it was suspected that the calender roll was responsible for this caliper variation, the exact magnitude and cause of the variation needed to be identified. Full length deckle strips and MD reels from the same parent roll were analysed off-line. 'True' caliper profile in the cross direction of consecutive deckle strips showed the presence of an S-shaped profile which changes direction between deckle strips (Figure 9), suggesting a calender alignment problem. This was subsequently confirmed in analysis of MD reel.

Figure 10 shows the zoomed caliper profiles measured off-line in the machine direction over an 8 m length of paper. At approximately every 2.1 m wavelength, there was a clear periodic variation in caliper when the paper was made with the old calender roll.

Frequency analysis of the MD data of both basis weight and caliper, showed a very sharp peak at 6.05 Hz frequency or at 2.07 m wavelength *only* on the caliper spectra, that was absent from the basis weight spectra (Figure 11). This confirmed that the source of caliper variation is independent of basis weight variation and was due to some rotational element on the machine. Off-line analysis of products made on the same machine, but at different machine speed showed the presence of a caliper peak (similar amplitude of variation) with different frequency, but of the same wavelength, confirming the source of caliper variation in the machine direction to be due to a rotating roll, the circumference of which was exactly 2.07m . The excessive caliper variation in the machine direction was due to the calender swimming roll.

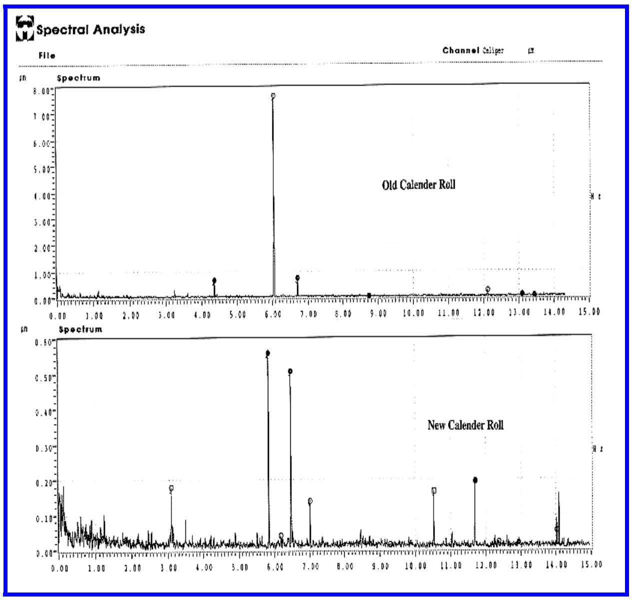

Figure 11 FFT Spectra of MD caliper Data

It appeared that the design of the calender roll was faulty at the time this roll was commissioned. Over time, the problem accentuated to a level where product quality convinced the mill to replace the calender roll. After the old calender roll was replaced with a new unit, a similar grammage product made on this machine at the same machine speed was analysed off-line (both full length deckle strips and an MD reel cut from the same deckle position) using the Tapio profiler. Comparison of the caliper profile in the machine direction with the new calender roll is shown in Figure 10 (bottom graph). Fast Fourier Transform (FFT) spectra of MD caliper data with the new calender roll is also shown in Figure 11 (bottom graph). It is clear from these figures that the significant periodic variation originally present had been eliminated. This was reflected in the reduction of the value of the coefficient of caliper variation (of an MD reel measured over a length of 3000m) with the new calender roll (2.0% vs 6.84% with the old calender roll). Although the FFT spectra of MD caliper data with the new calender roll showed the presence of the same frequency peak as that with the old roll, the amplitude of peak was about 13 times lower (0.6 μ vs 8 μ).

A similar problem in caliper variability in the machine direction of paper *made on another machine* with new calender rolls was analysed off-line using the Tapio profiler. In this case problems with both the calender rolls were identified. Analysis of a baby reel cut from close to the back edge of the machine showed that the magnitude of the variability was worst on the backside of paper rolls. This proved that sampling methodology is very important in diagnosing potential MD variability problem.

Case 2 : CD Basis weight problem

This example is based on a lightweight product that had excessive basis weight variation in the cross direction. Off-line measurement and analysis of such data was used to identify the source of the variation. Figure 12 shows that the CD basis weight profile of machine G in the CMD is very poor, with the presence of some periodicity. The FFT spectra of CD basis weight data is shown in Figure 13. A sharp peak at a wavelength of 550 mm was clearly identifiable. This wavelength is exactly four times the length of the slice spacing in the flowbox. The flowbox of this machine was not equipped with an automatic slice adjustment facility. It was revealed that while manually adjusting a slice, the operator bent the slice lip due to excessive force on the adjustment screw.

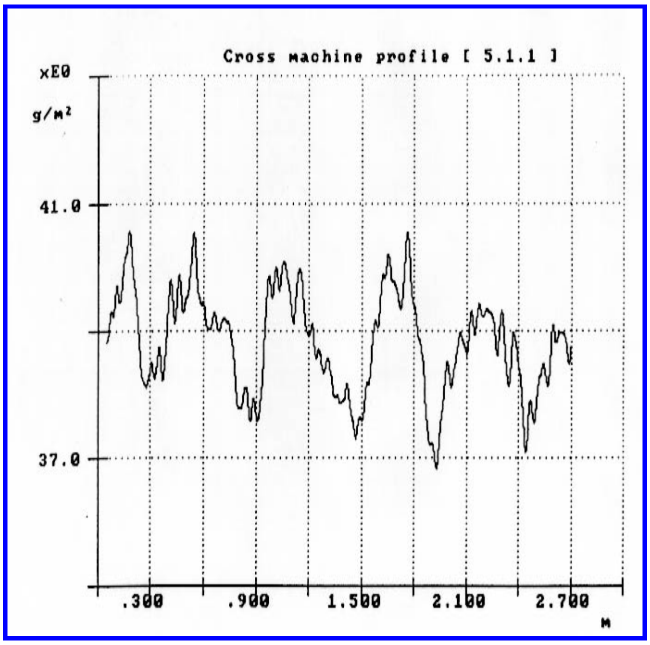

Figure 12 CD Basis weight profile of Machine G

This analysis result was also used to predict potential improvement in basis weight variability of paper made on this machine (G), if the existing flowbox (that is very old and had well-known problems) is replaced by another old flowbox. The flowbox was available to the mill due to upgrade of another machine (E) of the company. No trial was carried out on machine E to manufacture a product that was being made on machine G. Before the flowbox of machine E was replaced, basis weight variability of the lightest weight product made on this machine at 800 m/min machine speed, in CMD was measured using off-line Tapio profiler. Several realistic assumptions were made. One such assumption was applicability of the linear relationship of basis weight variability in CMD with speed for same grammage product made on same machine (machine D in Figure 3) on machine G.

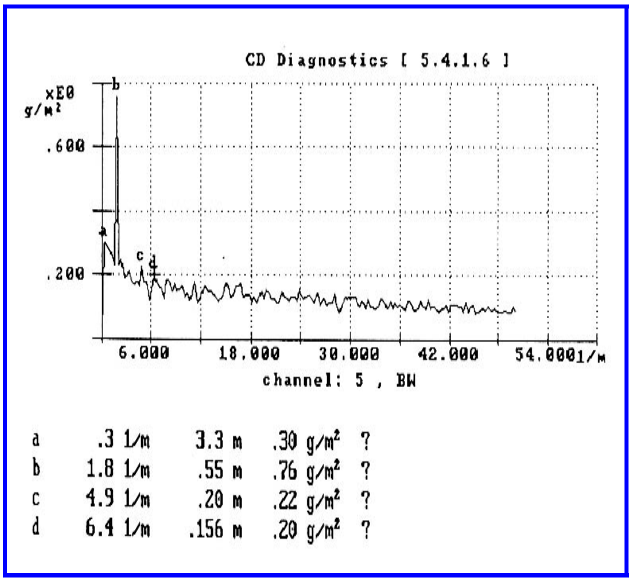

Figure 13 FFT spectra of CD basis weight of Machine G

Figure 14 shows the linear relationship of coefficients of variation of CD, MD and residual components of total coefficient of variation in the CMD as function of machine speed. The true basis weight coefficients of variation (CD, MD and residual components) of machine E and that of machine G (for a range of products) are also shown in this figure. For machine G, operating at less than half of machine speed of machine E, the CD variability was higher than that of machine E. The assumption is made that the gradients for each component of the CMD variability measured for machine D are applicable for the old flowbox from machine E. Extrapolation from the residual, CD and MD coefficients of variation at 800 m/min (operating speed of E) to around 370 m/min (operating speed of G) shows the approximate effect of replacing flowbox G.

The estimated reduction in the basis weight residual coefficient of variation for machine G would be between 60% to 70%, if its existing flowbox is replaced by that of old flowbox of machine E. Although the estimation was based on realistic analysis and measured data, the mill did not opt for this replacement, mainly due to other logistic problems associated with the old flowbox, such as transportation cost, width of the flowbox and stock entry points. Nevertheless, this demonstrates that such analysis based on off-line measured basis weight variability can be used for similar application.

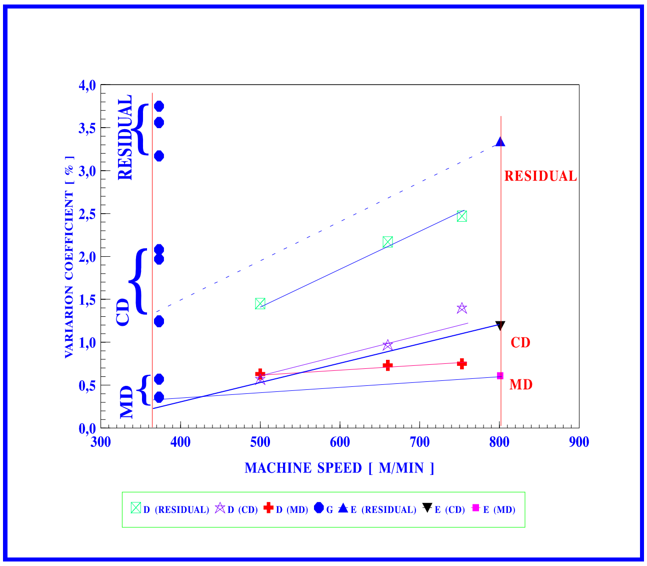

Figure 14 Estimated improvement in BW coefficient of variation for old flowbox of E operated at G machine speed

Case 3 : MD Basis weight Problem

The example presented in this case is based on excessive basis weight variability in the machine direction for a multi-ply linerboard product. The mill reported that the unacceptably high MD basis weight variation was evident only when all the forming stations were operational. For lightweight grade products made on this machine, the MD variability was not as severe as that of heavier grades (two forming stations are normally not used for lighter grade products). Following a request from the mill for off-line analysis to try to pinpoint the source of this variation, three MD reels cut from the front centre, centre and back centre of the same parent roll were analysed. The basis weight coefficient of variation in the machine direction of the roll from the back centre was much higher. FFT analysis of the off-line measured MD data showed the presence of a significant peak at 13.0 Hz frequency and a minor peak at 6.45 Hz frequency in the basis weight spectra, as shown in Figure 15. The same peaks were also present in the caliper spectra, but were not present in the top and bottom gloss spectra. This confirmed that the caliper variation in machine direction was due to the basis weight variation.

The wavelength of the 13.0 Hz frequency variation (and also that of 6.45 Hz) was too small to be attributable to any rotating roll on the machine. The source of the basis weight variation was consequently pointed towards the stock approach system. The mill routinely carries out condition monitoring of all its rotating elements of the stock approach system and the machine elements. Frequency analysis of the condition monitoring data matched one of the frequency variation (at 6.45 Hz frequency) that was identified from the FFT analysis of off-line measured MD basis weight data. The source of this variation was found to be the primary centi-screen. The source of the significant variation at 13.0 Hz frequency has not been conclusively identified yet. Further off-line analysis of MD reels from different grammage products and same grammage product, but made at different machine speeds, has been planned.

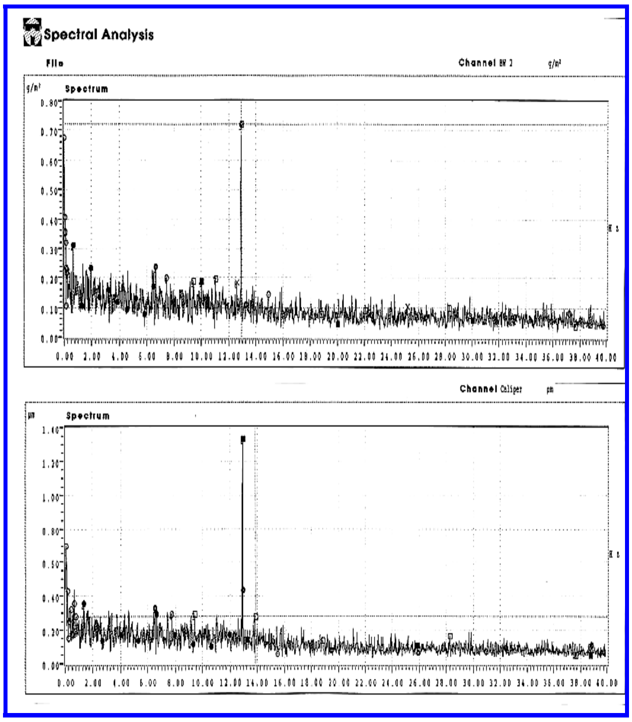

Figure 15 Basis weight and caliper spectra of linerboard product

CONCLUSIONS

Measurement of fundamental paper properties such as basis weight, caliper and paper gloss using an off-line instrument and the analysis of such data have been used successfully in diagnosing and subsequent troubleshooting in paper machine and stock approach systems to improve paper uniformity. Case studies showed that this technique is a powerful tool in improving variability in paper properties. Paper formation measured from analysis of off-line measured basis weight and light transmission data correlates very well with the specific formation measured using the Ambertec.

Regular audits of paper uniformity using off-line measurement of paper properties offer tremendous potential to paper mills for optimisation of paper machine, coater and supercalender. Benchmarking of the performance of a new flowbox and comparison of flowbox stability can also be established from such an analysis. Accurate measurement of paper variability using an off-line instrument such as the Tapio profiler is becoming an industry standard to evaluate flowbox performance.

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REFERENCES

(1) Cutshall, K. – *Tappi J*. June : 81 (1990)
(2) Burkhard,G. and Wrist,P.E. – *Tappi J.*, 37(2):613 (1954)
(3) Burns, J.W. – *Tappi J*. 57(12):143 (1974)
(4) Mardon, J., Lai, R. and Tkacz,A. – *Appita Annual Conference*, p669 (1996).
(5) Ghosh, A. – *Appita Engineering Seminar*, 1988.
(6) Perento,J. and Hilden, K.K. – *Tappi Coating Conference*, p177 (1996).
(7) Graber,K.B. and Gottsching, L. – *Jahrgang*, 32(10), 445 (1978)
(8) Sze, D. – Tapio Users' Club Seminar held at Tampere, Finland on June 03-04, 1997.
(9) Sara, H. – *Ph.D. Thesis, Helsinki University of Technology*, 1978.