Next generation optical caliper sensor technology

Rambod Naimimohasses (ABB Ltd), Ake Hellstrom (ABB Consultant)

ABSTRACT

Caliper measurement and control is a vital part of papermaking. But this measurement can be a challenge. Over the years, various mechanical and optical sensors have been invented to achieve the best combination of accuracy, no sheet damage and reliable operation.

Some caliper sensors utilize laser triangulation. There are several inherent accuracy problems in this method. One particular problem is due to light interaction with semi-translucent cellulose fibers or coatings of the paper being measured. This can allow the light to penetrate the paper body instead of being reflected from the true paper surface. Consequently, the distance to the actual paper surface cannot be determined accurately. Grade-dependent and process-dependent calibrations or other compensations may be required when utilizing a laser caliper sensor.

In this paper, we present a new, optical on-line measurement that measures caliper without laser triangulation, thus vastly reducing errors and provide a more reliable measurement. This new method can also detect very small scale variability of the sheet. Findings on production paper machines will be discussed.

Summary

Our new Optical Caliper Sensor is based on a confocal displacement technique and thus avoids many of the drawbacks of laser-based caliper sensors. The sensor is ideal for applications where the sliding skis of traditional caliper sensors gives rise to problems. We describe the principle of the new sensor and its inherent advantages over current offerings. Field measurements that not only provide a previously unobtainable view of small paper detail but also surpass current sensor performance are also described.

Introduction

Accurate caliper measurement and control are critical for defining paper quality. Traditionally, this has been achieved through the use of dual-sided, contacting caliper sensors. Some applications pose tremendous challenges for the contacting caliper skis. We pioneered non-contacting sensors with airbearings in the late 1960s.These offered simplicity but had marginal accuracy and resolution performance on high speed machines.

QCS suppliers have, in the last few years, been focusing on *optical* caliper sensors. Most commonly, these sensors utilize a laser triangulation technique. This method, however, has its own problems in obtaining a consistent and accurate measurement

We have chosen quite a different optical approach which dispenses with lasers and which provides greatly improved measurement accuracy and stability. This new sensor, the latest in our 50-year history of pioneering on-line paper quality measurements, finally provides papermakers with the precision tool to measure and control caliper even for some quite demanding paper grades.

Current laser triangulation technology limitations

Considerable effort has been invested over the past decade to develop a single- or dual-sided non-contacting caliper sensor applicable to the paper industry. To date, much of this effort concentrated on laser triangulation displacement sensors. This method has found acceptance in other industries such as metals, rubber and plastics, in measuring thickness, non-destructive testing and surface profiles.

The method compares a physical gap and a laser triangulation distance measurement to the free sheet surface. The triangulation works by focusing a laser beam onto the surface being measured and detecting the reflected light via an imaging sensor located at an oblique angle to the laser (see Figure 1). The distance from the sheet surface can then be determined from analyzing where the image is formed on the imaging PSD or CCD detector.

This method works extremely well for surfaces that have no penetration issues such as metals. However, if the light penetrates into the bulk material, as is the case with paper, then the method will have difficulties determining the true surface location and hence give a false distance measurement.

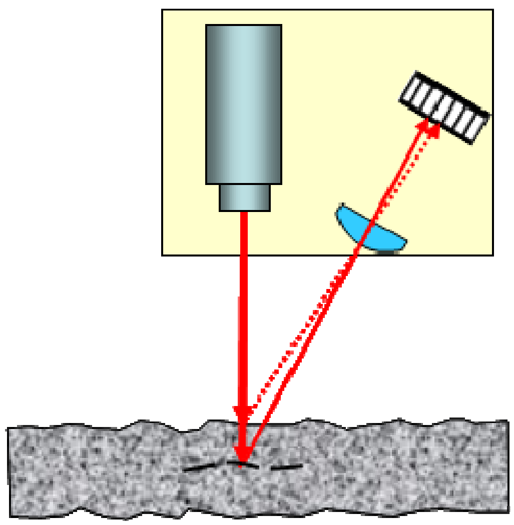

Figure 1. Laser triangulation paper measurement.

Indeed, this was observed when we built and tested their first laser triangulation caliper sensors in the 1990s. One of the key observations made was the need to calibrate the sensor according to paper type. Since the sheet properties will vary to some degree while in-grade, this implies a risk of unstable measurement or profile errors in a paper production run.

The light penetration can be easily demonstrated by measuring paper samples with both contacting and laser sensors in tandem on a dynamic paper test machine measuring a combination sheet of five different paper grade sheets taped together into one endless loop. Figure 2 shows just such a comparison of dual sided contacting vs. dual sided laser triangulation caliper sensors. The loop consists of three different fine writing products, one bag Kraft product and a card stock product. We observed some degree of agreement between contacting and laser on the three fine writing sheets, although with errors up to 10 microns, but there is a major discrepancy between the laser and the contacting sensor level on the card stock and brown Kraft sheet. It is noted that the laser reads quite thin caliper on both of these samples, about 40 microns too low for the Kraft sheet. This test was also repeated using different sheets from the same grades of paper. The measurement results on the second test are almost identical to the first test.

The light scattering and penetration issue has been verified by other researchers [1],[2],[3]. It has been difficult to achieve a common calibration for different paper grades and surface conditions on laser caliper sensors. The sensor errors between different sheet conditions can be significant. For some cases on thin paper grades, the corresponding laser sensor caliper errors can approach 50% of the sheet thickness.

Because of these problems, laser sensor applications may not achieve sufficient accuracy for reliable process control. The sensor may require special grade to grade calibration and periodic re-tuning, or different corrections across the profile. This is because the light penetration depends on process conditions that may change. This includes for instance, fiber type, fiber length, fillers and coating amount and constituents, calendering line pressure profile, and more. As result, some laser sensors may also need to operate in tandem with a periodically engaged contacting caliper sensor to refresh the laser sensor for both absolute and profile shape calibration.

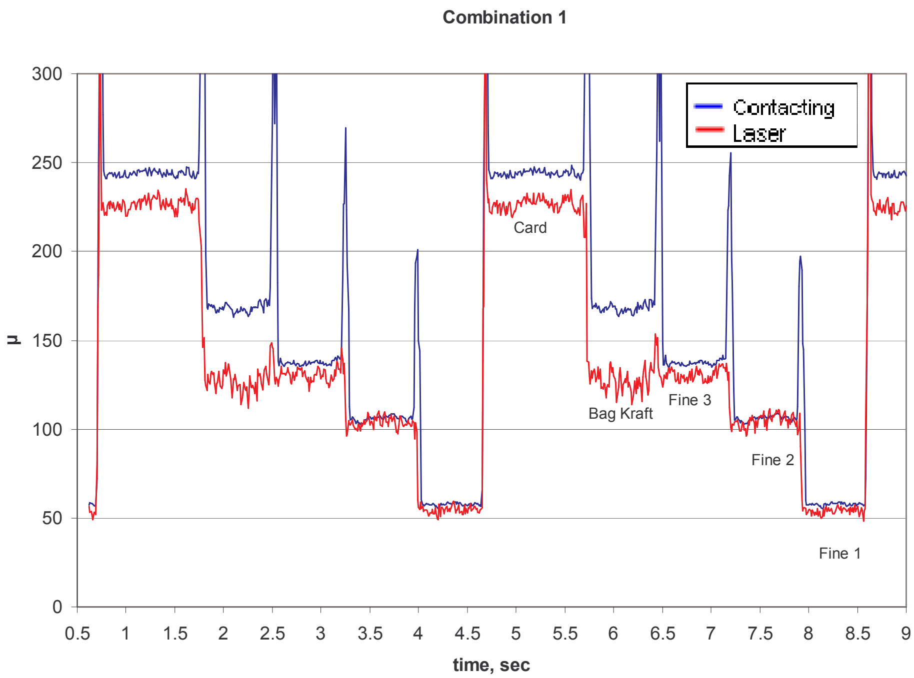

Figure 2. Performance of laser triangulation vs. contacting caliper on different grades.

Next generation of Optical Caliper Technology

We have taken steps to develop a sensor that solves the abovementioned accuracy problems. The project started by numeric optical modelling of light interacting with cellulose fibers at different geometries [4],[5]. We gained model confidence and practical experience by lab testing. We studied very different optical technologies and results achieved in other industries. It soon became clear that laser triangulation was not the best tool for precision paper measurement.

The optics approach for our Optical Caliper Sensor is, therefore, not based on laser triangulation. It is based on a confocal displacement method (see Figure 3). The term "confocal" implies that one very small spot of the surface is in sharp focus for both source and detector by a shared lens and fiber optics delivery. The measurement system analyzes the reflected light and the maximum detection peak is due to the light from the top surface, while all other reflections are out of focus and not detected. This technology has made recent advances for applications in microscopy, thin-film research and semiconductor manufacturing. It has also been demonstrated in research facilities for study of sub-μm paper surface topography.

The symmetrical illumination and common optics path for source and detector ensures that surface features do not adversely affect the measurement due to the shadowing effect experienced by laser triangulation.

As a result, this Optical Caliper Sensor senses the true paper surface, thereby vastly reducing the light penetration errors typical of laser-based caliper sensors (see Figure 3).

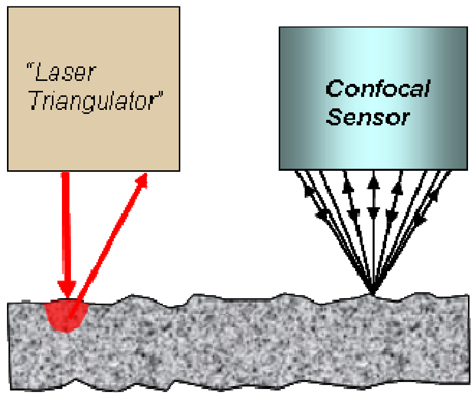

Figure 3. A confocal sensor vastly reduces error from light penetration that may occur with laser triangulation.

Figure 4 shows a topographical image of paper taken by the confocal displacement technology. It is apparent that individual fibers are always detected clearly and in sharp focus. The fiber translucency and related light penetration is not a problem for this technology.

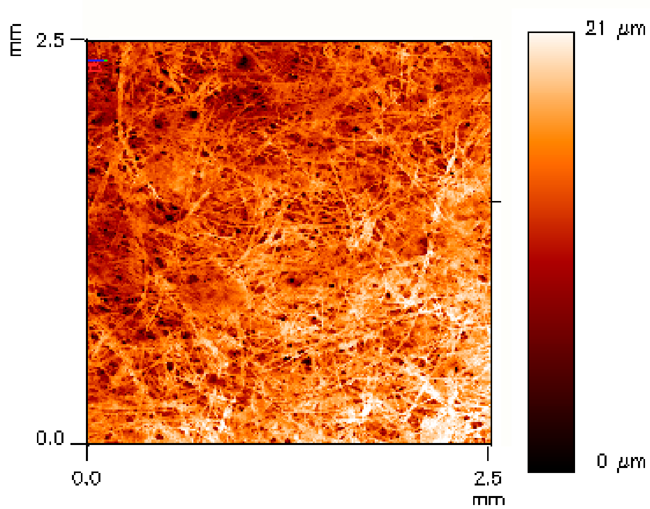

Figure 4. Image of a paper surface using confocal displacement technology employed in the Confocal Optical Caliper Sensor

Optical Principle

The confocal method [6] works by sending broadband light from a high power white LED source via fiber optics through a lens system to project a small spot (12 µm) on the sheet surface. The lens system is designed to provide a high level of chromatic aberration. This focuses each spectral component of the light at different distances from the lens. The reflected light from the sheet returns on the same path through the lens and the optical fiber. The shared optical path for send and receive makes this a more accurate method than laser triangulation. A fiber optics splitter at the end of the cable feeds the received light into a spectrometer. The first prominent peak in the color spectra pinpoints the first surface of the paper sheet. Paper colour and brightness may change intensity of reflected light but only the wavelength is of importance, and this is only related to distance. A dedicated DSP signal processor evaluates the received spectra at 4,000 measurements per second. (See Figure 5)

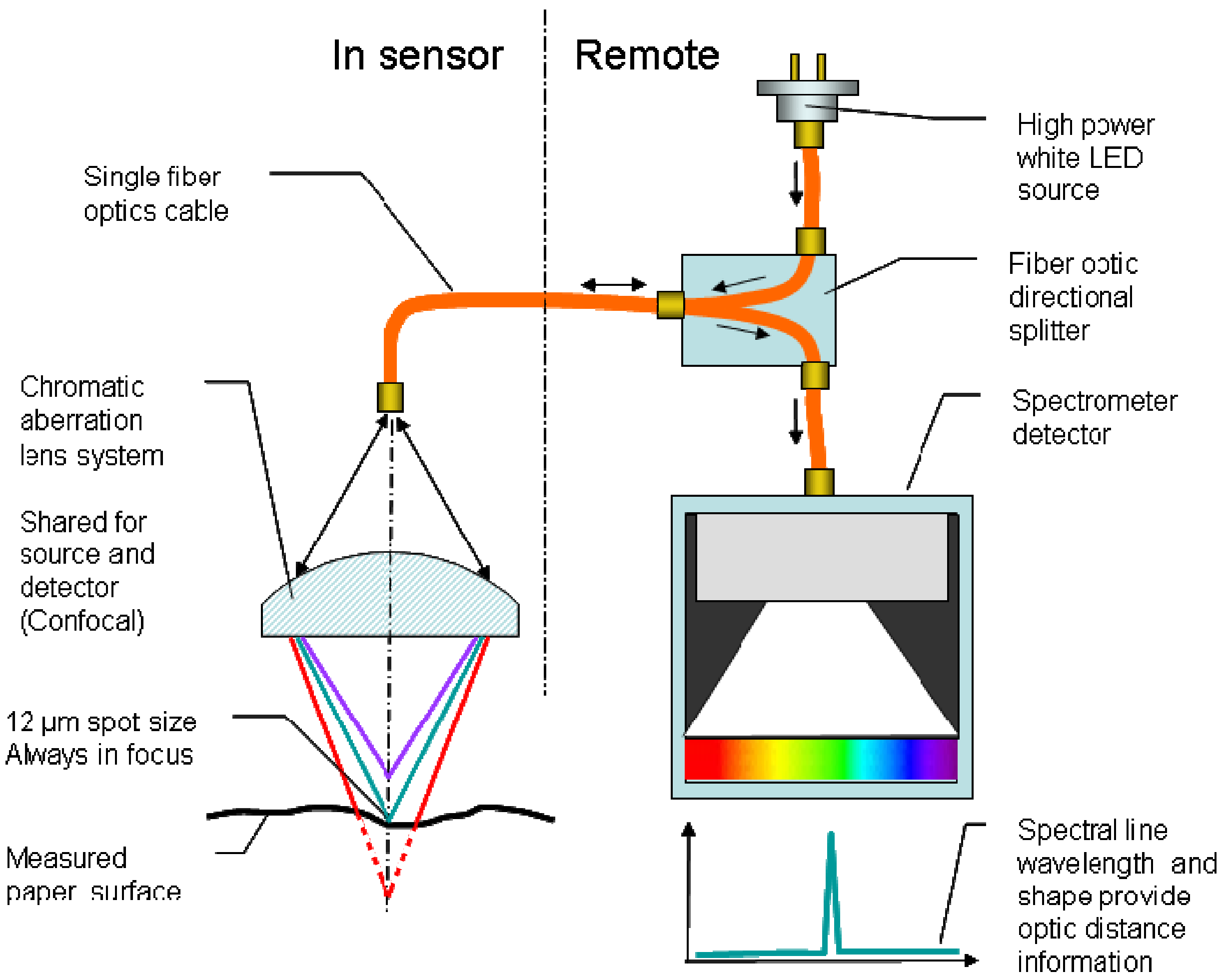

Figure 5. Confocal Optical Caliper Sensor principle.

A special spectral shape analysis algorithm further improves agreement between sensor and laboratory, even for sheets with pronounced surface topography.

Figure 6 illustrates the sensor's response for a variety of paper grades and Mylar samples with the same calibration setting applied for each sample. The samples cover tissue, SC-A, coated and uncoated, liner board, newsprint, card stock as well as glossy grades. This graph shows a remarkable linearity over a wide range of samples implying that the measurement does not require any grade-dependent calibration. The thin tissue grade had fibers that were read high because of unbounded individual fibres that were physically extending outside the sheet. This test was performed in a lab environment on sheet samples and may not include all possible disturbances that may occur in a production environment, but it certainly illustrates the basic performance of this new technology.

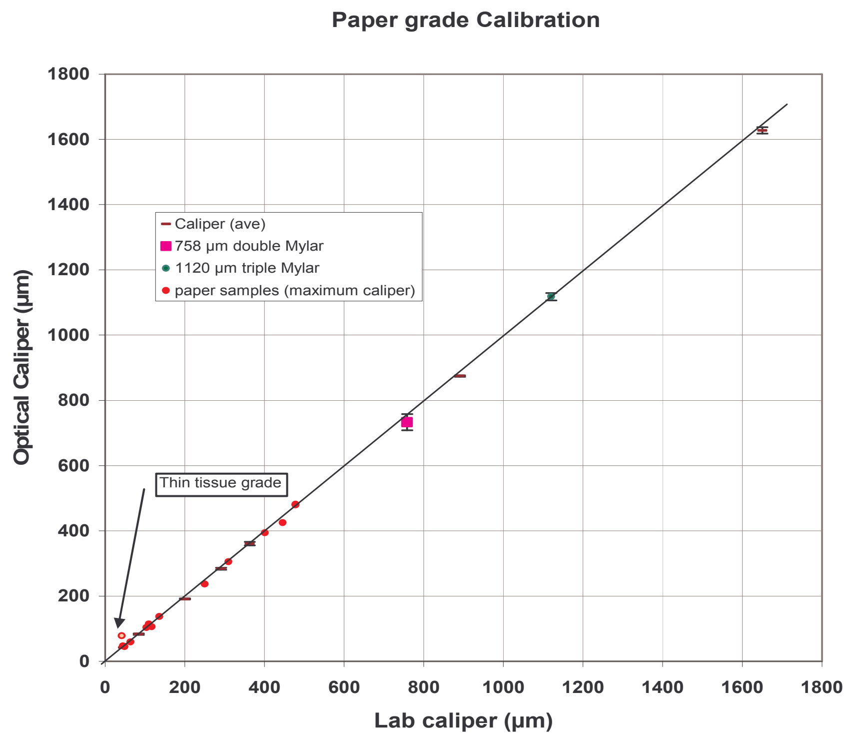

Figure 6. Confocal sensor reading for a variety of sample types and thickness levels, with the same calibration.

Gap measurement and sheet stabilization

In order to measure the sheet caliper, an accurate measurement of the sensor gap is as important as the optical measurement. In Figure 7, a cross-section through the two sensor heads is illustrated in principle. The reference distance between the top and bottom heads is sensed by a specially-designed magnetic inductance technology which is exceptionally accurate and stable. The difference between this primary magnetic gap measurement and the optical distance measurement determines the caliper measurement. Furthermore, there is a secondary magnetic sensor for 3-axis head alignment diagnostics and compensation. This feature makes the mechanical setup user-friendly and robust, and enhances profile accuracy by multi-axis residual error correction.

A well-controlled sheet position is essential for any optical caliper measurement. The sheet in this sensor is positioned accurately and kept very flat by means of a sheet stabilizer in one sensor head. The stabilizer contains a ferrite target for the primary magnetic gap measurement and an optical target where the optics is focused [6].The sheet control is achieved by means of dual concentric rings with a very light vacuum. This will gently stretch the sheet and remove any wrinkles in the optical measurement zone without marking the sheet or allowing build-up of coating or contaminants. As a result, the Optical Caliper sensor is applicable to demanding grades such as newsprint, coated, super calendered, and fully-recycled grades. (See Figure 7)

Super-smooth ceramic coatings and hard materials are used in the sheet stabilizer plate to prevent build-up and sheet marking, and to provide excellent wear resistance. The large vacuum zones are designed to prevent accumulation of fillers and coating and reduce or eliminate the need for maintenance cleaning.

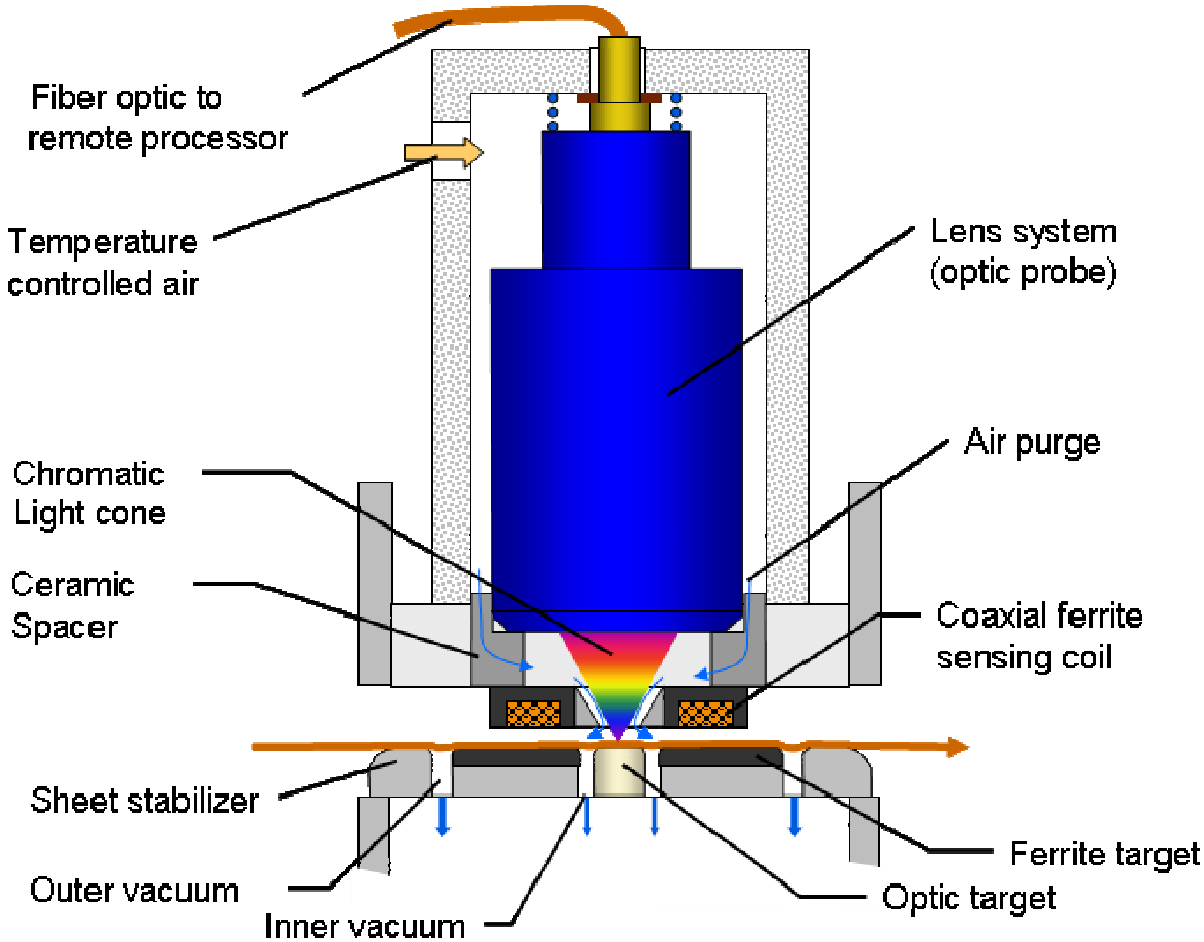

Figure 7. Simplified sensor cross-section

Signal Processing

An optical signal analyser is connected via fiber optics to the active head. It includes the optics source and detector, and is equipped with a DSP and microcontrollers that performs all front-end, high-speed signal processing for optical, magnetic and diagnostic signals. The analyzer is connected via a dedicated Ethernet link to the Network Platform measurement processing center. The Network Platform is connected to the host QCS system via Ethernet QCS-LAN. The maximum measurement speed attainable with this arrangement is up to 4000 readings / second.

Measurement Results

The Optical Caliper Sensor was first tested on a large, dual-side coated LWC machine. We obtained exceptional agreement with the contacting caliper sensor. Figure 8 displays a high resolution CD profile comparison between the optical caliper (OC) and the contacting caliper sensor (GT). This profile was taken from inspection data during the test production period.

This machine produces a nearly 10 meter wide sheet running at more than 1600 m/min, with inline multi station coating, as well as a large inline gloss calendering section. Despite the high speed, a thin sheet and considerable vibration, the optical caliper measurement agreement with the contacting sensor was excellent.

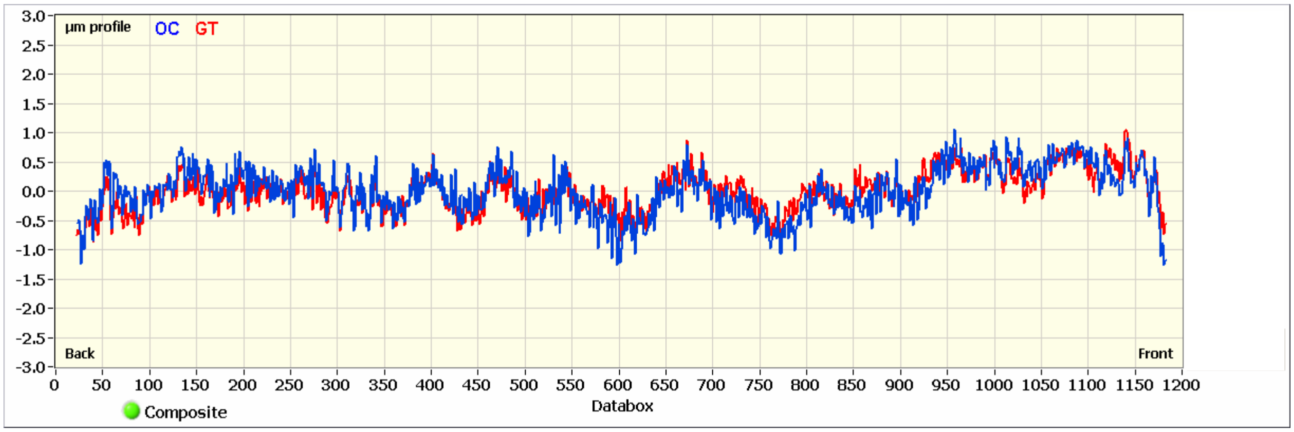

Figure 8, On-line high resolution composite profiles on dual-side coated LWC paper.

It can be seen that the profile deviation between the two sensors is typically better than 0.5 microns on this LWC process. We can also see that the optical sensor detects small scale variability more clearly than the contacting sensor. One of the main concerns with this customer was potential sheet marking by the sheet stabilizer. The process was monitored daily for sheet marking. No marking was observed, due to the stabilizer's light sheet contact.

The second, permanent, installation is on a large, 100% recycled furnish newsprint machine. Figure 9 shows the sensor performance compared to contacting. The machine produces a 9.3 meter wide sheet running at 1,800 m/min. This process can pose problems for contacting sensors such as occasional build-up on the contacting sensors or other mechanical factors that may cause degradation in measurement or creating sheet handling problems.

The profile deviation between contacting and optical measurement is better than 0.5 microns.

The optical caliper was installed in December 2008 and has been used in production on this machine since early January 2009. After one month of sensor evaluation, the optical caliper sensor began to be used for CD caliper control. The sensor has been used for CD control since mid-February, 2009. Since then, the paper maker reports improved reel building and profile variation is reduced compared to the results from the contacting sensor. Furthermore, the sensor has proven nearly maintenance-free on this process and does not require any special cleaning or periodic adjustments. Sensor profile agreement with the customer's laboratory has also been improved, with agreement better than 1 micron and very good long term sensor stability..

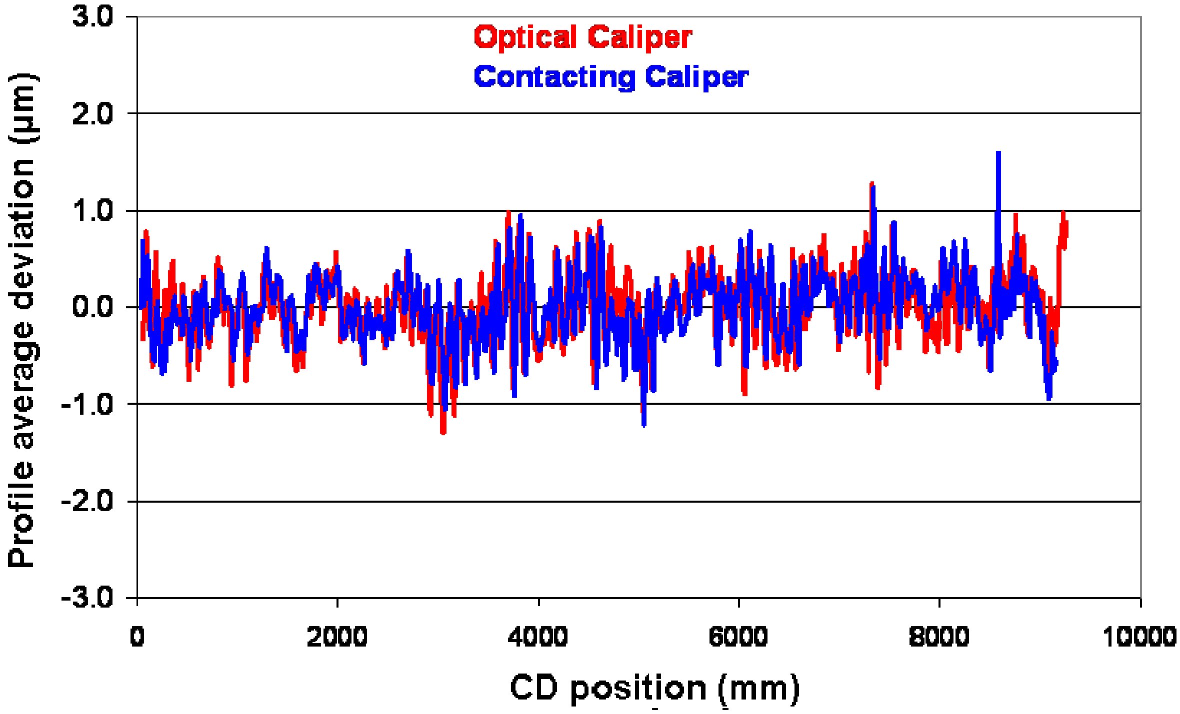

Figure 9. On-line performance on fully-recycled newsprint grade.

Conclusions

The new confocal principle Optical Caliper Sensor has been shown to provide a robust, reliable and very accurate caliper measurement on two different and demanding process applications. As the sensor avoids some of the inherent measurement issues of laser triangulation, it provides papermakers with an improved instrument to measure caliper in processes where dual-contacting ski devices experience difficulty. This sensor opens up a new era of caliper measurement technology.

Acknowledgements

The authors would like to thank the kind support of Peter Kluttig, Tim Melzer and personnel of StoraEnso Sachsen GmbH of Eilenburg, Germany.

We like to thank Nippon Paper Industries for their co-operation in providing a site for us to conduct tests on the new Optical Caliper sensor. Thanks to the provision of this facility, the tests were able to be successfully carried out.

We also like to thank YEC for facilitating the contact between Nippon Paper Industries and our engineers

And, thanks to Kari Saarinen, ABB Corporate Research, Sweden, for optics analysis and mathematical modeling of light / fiber interaction.

References

[1] Reijiro Nakano, “Non contacting caliper measurements (Laser caliper sensor)”, 11th paper manufacturing technical seminar, Japan TAPPI vol. 60, no.. 2, 2008 p 169-175 .

[2] Y.J. Sung, C.H. Ham, O. Kwon, H.L. Lee and D.S. Keller, “Application of Thickness and apparent density mapping by laser profilometry”, 13th Fundamental Research Symposium, Cambridge, September 2005, p 961-1007.

[3] H. Holik, “Handbook of paper and board”, 2006, ISBN 3527309977, p 409.

[4] K. Saarinen and K. Muinonen, Light scattering by wood fibers. Applied Optics 40(28), (2001) 5064-5077

[5] K. Muinonen and K. Saarinen, Ray optics approximation for Gaussian random cylinders. Journal of Quantitative Spectroscopy and Radiative Transfer 64 (2000), 201-21

[6] US published patent applications 20090059244, 20090056156 and 20090059232; all titled “Web Measurement Device”. USPTO, March 5, 2009

Author contacts:: Rambod.Naimi@IE.ABB.com (Dundalk, IE) phone +353 429388366

Ake.Hellstrom@US.ABB.com (Columbus OH, US) phone +1 614 4572984