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Online Surface Topography Characterization
Technique for Paper and Paperboard using Line
of Light Triangulation

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Online Surface Topography Characterization for Paper and Paperboard using Line of Light Triangulation Technique

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ABSTRACT

In the Paper and Paperboard industries the surface topography is the essence of the production and constant efforts are being made to improve it. Accurate measurements of the surface topography are equally important in order to monitor and maintain the surface quality to be as smooth as is possible throughout the production. Generally, the topography is considered as being the most decisive paper property which has an effect on both the printability and gloss, and also influences the perceived surface quality. Presently the surface is being measured in a laboratory by methods which are mainly based on air leak, stylus and optical techniques. The laboratory measurements have a number of limitations and the most critical is that only a few samples are measured which cannot accurately represent the topography of the entire tambour. Furthermore, the majority of the lab equipment measures the surface roughness in a single variable of average roughness Ra or Rq and this has proved to be inadequate for characterizing the surface quality comprehensively.

The online topography measurement of a paper web moving at high velocities is an important and challenging research area. The online setup can be arranged either in the Cross Direction (CD) or the Machine Direction (MD) on a paper web. In order to discover the topography differences between the CD and MD, a case study was performed in the laboratory for samples of newspaper, light weight coated papers (LWC), coated paperboards and uncoated paperboards. The study reveals that the measurements in the CD yield higher topography details for shorter wavelength roughness.

The online surface measurement is presented by using a recently developed prototype, the Online Topography device (OnTop), which was designed on a line of light triangulation technique and scans the paper along the CD. It gives topographical information while the paper is being processed which can be of assistance in making the surface smooth and the process efficient. For accuracy and validity, the measurements from the OnTop were compared with the available offline industrial devices and a linear regression match between the offline and online measurements was found in range 82% to 96%. The online topography characterization was successfully achieved for various grades of paper and paperboards, including the samples from the same family of material and quality grades, such as the edge and the middle position coated paperboard reels, with an average roughness Rq and in a wide wavelength spectrum from 0.1 to 10mm. The thesis also explains the necessity for and the essence of online topography in the paper industries and describes the design techniques employed in order to develop the prototype.

The online experimental results, by using OnTop, prove that the exploitation of a simple laser triangulation technique can be a valuable application especially in the paper and paperboard industries and has potential in relation to the other industrial applications.
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Since my childhood, the wish to become researcher appeared to be going to be one of my many broken dreams and my belief that I am living in a world of dreams in which dreams cannot become true, grows stronger as life continues. However, I gained admission to the research programme as Master in Electronics Design in Mid Sweden University and it was here that I first met Professor Bengt Oelmann and yes, he impressed me and shown me the research facilities in the department which was the starting point to losing my belief that I was living in a dream world. In the initial research projects Dr. Göran Thungström, Dr. Kent Bertilsson and Dr. Benny Thörnberg have encouraged me at every step and have maintained my motivation and thus the roots of my research started to grow. My dream became true when Professor Mattias O’Nils offered me the opportunity to enter the real world of research and offered me the chance to pursue a four year Ph.D. study. The guidance to face real world challenges and motivations provided in the supervisions of Professor Mattias O’Nils, Dr. Jan Thim and Dr. Anatoliy Manuilskiy were the backbone to achieving the milestones in the research project. The assistance provided by Krister Alden is gratefully acknowledged. The research work has been greatly supported by the provision of experimental materials and facilities from the Paperboard Mill at Iggesund, by the Manager Paperboard Development Centre at Iggesund, Dr. Johan Lindgren and Joar Lidén of SCA Ortviken AB, Sundsvall, Sweden.

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Sundsvall, February, 2012

Mohammad Anzar Alam
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AFM ............. Atomic Force Microscope
ASME .......... An American National Standard, the American Society of Mechanical Engineers
CCD ............. Charge Couple Device
CD ............. Cross direction
CEPI ............. Confederation of European Paper Industries
FFT ............. Fast Fourier Transform
FRT ............. Fries Research & Technology GmbH
ISO ............. International Standard Organization
LED ............. Light Emitting Diode
M1 ............. Paperboard manufactured in Machine 1
M2 ............. Paperboard manufactured in Machine 2
MD ............. Machine Direction
NSOM ............. Near Field Scanning Optical Microscope
OnTop ............. The developed Online Topography Instrument
PQV ............. Metso Online Process and Quality Vision
Ra ............. Average Roughness
RMS ............. Root Mean Square
Rq ............. RMS Roughness
SEM ............. Scanning Electron Microscope
SFM ............. Scanning Force Microscope
SPM ............. Scanning Probe Microscope
STM ............. Scanning Tunneling Microscope
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LIST OF PAPERS

This thesis is mainly based on the following five papers, herein referred to by their Roman numerals:

Paper I  **Investigation of the surface topographical differences between the Cross Direction and the Machine Direction for newspaper and paperboard**
Anzar Alam, Jan Thim, Anatoliy Manuilskiy, Mattias O’Nils, Christina Westerlind, Johan Lindgren and Joar Lidén,

Paper II  **Online surface roughness characterization of paper and paperboard using a line of light triangulation technique**
Anzar Alam, Anatoliy Manuilskiy, Jan Thim, Mattias O’Nils, Johan Lindgren and Joar Lidén,

Paper III  **Online Surface Characterization of Paper and Paperboards in a Wide-range of the Spatial Wavelength Spectrum**
Anzar Alam, Jan Thim, Mattias O’Nils, Anatoliy Manuilskiy, Johan Lindgren and Joar Lidén
1 INTRODUCTION

1.1 THE SURFACE TOPOGRAPHY IN GENERAL

In 1932, the Nobel Prize in chemistry was awarded to Irving Langmuir for his contribution to surface chemistry. Since then, surface science has been recognized as an independent branch. However, there is also philosophical and literary evidence that solid surfaces were studied in the history (5th century B.C to 3rd century A.D.) [1].

Topography involves a wide range of surface geometrical irregularities and structural properties. Roughness is one of the components of the topography. Topography is a broad engineering field and is one of the essential quality parameters for the products manufactured in process industries including metal, textile, plastic, fibres, paper, paperboard and machine tool factories. It has a great impact on the quality assurance of machined parts [2] [3] and can affect their functional performance [4]. It is fundamentally important in the precision engineering [5], bioengineering, geomorphometry [6], optical technology and tribology [7]. Hence the surface quality is one of the critical parameters used for the acceptance and the rejection of a final product [5].

The surface topography is the essence of quality in the paper and paperboard manufacturing. Researchers involved in these industries are constantly endeavouring to improve the quality of the final product so as to achieve a high perceived surface quality. A detailed account and information concerning importance of paper surface quality are provided in section 3.1.

1.2 THE ONLINE SURFACE TOPOGRAPHY MEASUREMENT

The laboratory test equipment is fundamental for maintaining the quality and standard of the manufacturing products. In addition to the laboratory instruments, recent researches have been focusing on shifting the lab equipment to machine locations where the measurements can be acquired directly.

Paper and Paperboard mills already have many online parameters and real time devices still have significant potentials in relation to applications within paper industries. At the present time, an increasing amount of testing occurs directly online during the production. Online measurements will surely enhance the possibility for efficient process and product quality control. Therefore, industry would like to perform both process and product control online as much as possible [8].

The online monitoring and measurements of the moving paper surface at high velocities is an important challenging research area. Various innovative techniques and methods have been applied in relation to measuring online paper surface roughness. From these, optical techniques have proved to be the main centre of attention as they involve non-contact method. In optical design, the majority of techniques employ a high speed camera to capture the surface features. The optical measurement becomes complicated if the surface moves rapidly as in the case of
paper manufacturing where the paper web velocities reaches 2000 m/min or even higher.

Recently, a few online devices have been developed by industrial researchers. The majority of these either measures a very limited surface area or merely detects the surface flaws. Some of these available devices are capable of comparing the topography of the paper surfaces if the differences on the surface topography are high but difficulties arise when there are only minor differences. Thus, it has become necessary to design an online instrument that can measure the surface comprehensively in a wide topographical range.

The thesis describes online surface topography measurements and characterization using the recently developed Online Topography (OnTop) device. The OnTop was developed to measure the surface topography in real time. Various grades of paper and paperboard reels were examined in a real environment at the Paperboard Pilot Coater. The thesis also explains the requirements and importance of online topography in the paper industries and describes the design technique used in the development of the OnTop. The online topography characterization was obtained in the traditional units of average roughness Ra, root mean square roughness Rq, and in a wide range of wavelength spectrum.

1.3 Main Contributions

This research work has made a contribution in the challenging research involving online surface topography measurement and characterization, with a particular focus on the paper and paperboard manufacturing industries. The following are the main contributions to the scientific community:

1. The investigation of surface topography differences in the cross direction and in the machine direction for various grades of paper and paperboard showing the importance of measurement and characterization in these directions.

2. A prototype non-contact device called the Online Topography (OnTop) was developed for the online paper web surface topography measurements. It is based on the line of light triangulation technique.

3. The surface topography measurement and characterization of the paper and paperboard were achieved as average roughness Ra, root mean squared roughness Rq, and in a wide range of wavelengths spectra from 87 µm to 10 mm.

4. The technique and the processing method adopted in the design of the prototype allowed the whole reel measurement to be made meter by meter on the paper web, moving at high velocities in real time.

5. The real time surface topography characterization has shown the capability to extract and measure the surface irregularities components such as roughness, cockling and waviness.
1.4 **Thesis Outline**

Chapter 1 provides an introduction, background information and the contribution to the scientific communities. Chapter 2 describes the laboratory instruments, the conventional topography measurement techniques and their limitations. Chapter 3 provides information about topography and its components while chapter 4 describes the current challenges in measuring the online topography, the motivation behind this project and related research. Chapter 5 concerns optical online measurement techniques, chapter 6 the measurement of an online surface profile and its statistical analysis. Chapter 7 is devoted to investigate paper surface topography differences between the CD and the MD. Chapter 8 describes an overview of the OnTop development technique and its accuracy estimation. Chapters 9 and 10 present and describe in detail the online measurement characterization in root mean square roughness $R_q$ and analysis in the long wavelengths spectra.
2 THE CONVENTIONAL MEASUREMENT METHODS

The paper and paperboard surface quality measurements are mainly performed in laboratories and a large number of laboratory based instruments are available which have been used in industries and research facilities. The laboratory instruments can broadly be divided into two categories, namely contact and non-contact based. There are various methods to measure surface quality including Air Leak, Mechanical Stylus, Scanning Electron Microscopy (SEM), Atomic Force Microscopy (AFM), Laser optical scanning and Photometric stereo [9]. The majority of the instruments, with the exception of the air leak method, scans the surface and creates a surface profile in one or two dimensions, hence, are commonly known as profilometers.

2.1 AIR LEAK METHODS

Air-leak methods are standardized and have been used over the years in paper and paperboard industries and are considered as one of the reliable techniques. There are various air leak measurement methods of which Bekk, Bendtsen and Parker Print Surf (PPS) are widely used. There is a common basic working principle for all of these techniques. These instruments have a sensing head which comprises a ring shaped metal edge called an “annulus” as shown in Fig 1. When the sensing head is placed on the paper surface only the annulus touches the paper with a specified clamping pressure (198 or 490 kPa). The inlet air pressure is externally supplied to the sensing head. The pressure difference between the inside and outside of the head is kept constant by means of a pressure regulator. Thus the rate of air leak between the annulus and the paper surface determines the roughness of the sample.

Fig 2 shows a simple setup for the Bendtsen and Bekk methods. In the Bendtsen method, a paper sample is kept between the annulus and a flat glass disc. The Bendtsen roughness is measured by measuring the rate of air flow in ml/min.

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Fig 1 Shows the basic technique of air leak method. The measuring head with annulus (left) and the measurement setup (right) shows how air leakages estimate roughness value.
The Bekk instrument is the predecessor of the Bendtsen method which was built around a vacuum chamber. In this method a differential pressure (50.66 kPa [10]) is created between the paper sample and the smooth glass disc underneath the sample. During the measurement, air starts to flow from a higher pressure to a lower pressure of the vacuum chamber through the sample surface and the glass disc. Under this differential pressure the time in seconds is noted to pass an air volume of 10 ml. Obviously, a rough surface will take less time and a smooth surface will take more time. This method is well known for measuring very fine surfaces such as finished paper and fine coated paperboards. The Bekk method measures smoothness in sec/10ml unit as opposed to the Bendtsen roughness method.

The Parker Print Surf (PPS) is complicated modified version of Bendtsen air leak method. In this design the pressure on the paper surface was increased from 490 kPa to 1960 kPa in order to create a pressure similar to the printing nip. Thus the PPS method provides possibilities to characterize the paper surface prior to the actual printing in the press by maintaining the same printing nip pressure. The PPS instrument is calibrated to provide roughness measurements in µm unit.

The main disadvantages of all air leak methods, in general, are that they are only valid for laboratory measurements which give roughness in a single variable and these tests are destructive. They possess poor resolution and can characterize roughness only down to the macro level thus leaving a requirement for a micro-roughness instrument [11].

![Fig 2](image)

2.2 **The Mechanical Stylus Methods**

The dial gauge instrument was among the simplest and easiest to use. It is contact based, portable and good for field applications as shown in Fig 3 (left). The
mechanical contact based stylus instrument consists of a fine preloaded diamond tip which is mechanically dragged over the surface under test. The stylus tip traverses the surface irregularities and measures the topography along a line. The conventional mechanical stylus has a vertical resolution from 2 to 5 µm. The resolution of the stylus depends upon the diameter of the tip which can be around a few µm [12]. As shown in Fig 3 (right) at position 1 the tip diameter is sufficient to read the surface topography but this tip is unable to enter the features that are narrower than the tip width as shown in positions 2 and 3.

Fig 3  Dial gauge roughness instrument (left). Figure on right shows rough surface and mechanical stylus tip limitations.

Metal surfaces can consist of soft elements such as aluminium, gold, copper, etc. For such soft surfaces the diamond stylus can create significant scratches. A study into the damages on various soft metals was conducted by Meli [2]. In the study he used a stylus instrument with a 2 µm radius diamond tip and a load of 0.5 mN. He recorded the scratches on the various surfaces, as shown in Fig 4. The worst affected surfaces were aluminium and gold. Although the stylus has the potential to be used as an online profilometer, the key disadvantages of the device are its low resolution and destructive measurement.

A mechanical stylus is mainly suitable for Iron, Steel and any industry involving the use of hard metals. However, these instruments are now being replaced by non-contact measurement techniques.

Fig 4  A case studies to find out damages occurs on the surface of various metals if measured by mechanical stylus probe [2].
2.3 THE ATOMIC FORCE MICROSCOPE (AFM)

The Atomic Force Microscope (AFM) uses a very small probing force and can measure soft surfaces, including paper, without any damage. Its tip is very fine and exhibits measurements with very high vertical resolution within the nanometre range. The basic setup of the AFM is shown in Fig 5. It measures the forces between the tip and the sample surface. A fine tip is attached to the cantilever and is brought very close to the test sample. During the scanning of the tip, together with the cantilever, it moves upward and downward proportional to the surface roughness. When the tip approaches a valley, the attractive force causes the tips to move downward and in case of peaks it moves upward thus deflecting the photo detector position. A reflected laser from the reverse side of the cantilever is detected by a multi-segment photo sensor which generates an electrical signal according to the reflected beam position. The beam position change is proportional to the surface heights.

In a similar manner to the AFM, high resolution devices including the Scanning Force Microscope (SFM), Scanning Probe Microscope (SPM) and Scanning Tunnelling Microscope (STM) have been in use for research to investigate the surface topography at the molecular levels of the samples. An AFM profilometer creates a 2D and 3D surface map and, being non-destructive, is widely used where high resolution is required. Its limitations are its long lead-time before measurements, slow speeds and that it can only measure small areas etc. [13].

![Fig 5 Basic setup for AFM. A fine tip attached with cantilever moves up and down following the surface feature in the photo detector.](image)

2.4 LIMITATIONS OF OFFLINE MEASUREMENTS IN PAPER INDUSTRIES

There are a number of obvious disadvantages in laboratory based measurements including the following:

1. A few small pieces of samples are usually taken from the end of a tambour/reel which cannot truly represent the surface topography of the whole tambour [14]. There are not only large local variations over the tambour, but the rolling force and the speeds are reduced at the...
beginning and end of the tambour, thus yielding changes in the properties at the sampling position as compared to the rest of the tambour [15].

2. The laboratory report lacks many dynamic properties and abnormalities of the surface during the manufacturing process such as cockling and wide waviness.

3. The surface inspection in a laboratory often does not provide opportunities to make corrections in the process if the quality is not as per the customer requirements.

4. The conventional methods, for example, air leak is good for a laboratory but is not valid for online measurements. Mechanical contact stylus has poor resolution and conducts a destructive test, therefore, it cannot be applied in paper testing. AFM and other high resolution microscopes are sophisticated and designed for laboratory conditions, however, the non-contact optical instruments have a strong potential for online measurements.
3 THE SURFACE TOPOGRAPHY

3.1 THE SURFACE QUALITY IN PAPER AND PAPERBOARD

The surface roughness of paper and paperboard is recognized as being the most important paper property, in relation to the printability, coating and consumption of inks [4][16][17][18][19][20]. For example, the worth of a graphical paper product mainly depends on the perceived surface quality [21][22]. Roughness depends on paper properties such as gloss, uneven grammage distribution and friction [23][24][25]. Paper is often coated (single or double sided) and the amount of coating depends upon the surface quality of the base paper/paperboard. Paper process researchers have been endeavouring to improve the processing techniques in order to enhance quality of the manufactured paper. This is the reason why many processing steps for example calendaring, coating, multiple coating and hot calendaring are in fact undertaken mainly to improve surface smoothness [24] [26] [27] [28].

3.2 OFFLINE TOPOGRAPHY PROFILE

Offline high resolution optical profilometers, generally, scan the surface in a raster fashion, points by points. The scanning of the sample is illustrated in Fig 6. The line scanned along x-axes is a Line Profile. It contains surface height irregularities (z-axis data) along that particular line. Multiple of such line profiles are created in steps along the y-axis as the whole sample is scanned. Total line profiles represent the whole sample therefore are known as an Area Profile. The measurement resolution along the x and y-axes is also shown. This kind of scanning is common for laboratory instrument but not for online devices.

Fig 6  Shows how surface profiles are created by raster scanning the sample and constructing the line and area profile. Scanning resolution along x and y-axis is also portrayed.
3.3 **TOPOGRAPHICAL COMPONENTS**

Topography is the complex surface geometry consisting of multi-periodic signals disturbed by periodic and random components [29]. Common topography components are roughness, waviness and form/position-error [20][30]. In addition, a paper surface often possesses another irregularity called cockling. An attempt is made to show all the topography components in Fig 7. A real paper surface is shown in Fig 7(a) while (b), (c) and (d) are the separated topography components waviness, cockling and roughness respectively.

The standard organization ISO/ASME B46.1-2002 [30] has set standardized methods in order to characterize and evaluate the surface features. It defines the components of the real surface and methods in order to separate its components. The standards also describe the measurement methods using various profilometer.

3.3.1 **Roughness and Waviness**

Paper surface features, in a broad sense, can be divided into waviness and roughness as illustrated in Figs 7 (b) & (d) and are statistically represented in Figs 8 (c) & (d). Roughness is defined as the finer irregularities on the surface that can be caused by processing methods or the material. Roughness is a short and narrow spaced deviation and waviness is a long and more widely spaced deviation phenomenon [31][32][33].

The topography components can also be explained in spatial wavelengths because the surface consists of a range of spatial wavelengths. The shorter wavelength ranges represent roughness while the longer as waviness. Fig 8 is the plot, in a logarithm scale, which shows the separation of the surface topography components in the wavelength spectrum. The fine length-scale phenomenon of roughness can further be divided into two sub categories. Roughness, within 0.1 mm length is due to fibres so it can be classified as fibre-roughness and roughness from 0.1 to 2 mm length is due to bundles of fibres therefore can be called fibre-network roughness. Waviness on the paper surface can appear after 2 mm. While Reis and Saraiva [32] describe roughness scaled between 1 µm to 1 mm and waviness above 10 mm. However, there is no strictly defined boundary to separate roughness and waviness as the range can vary depending upon the type and material under tests. For example for thin paper, waviness can appear after 2 mm and for thick paperboard it can be above than 10 mm. It is clear in Fig 9 that waviness (b) is separated by applying a low pass filter to the original raw profile (a) while roughness (c) is obtained by applying a high pass filter.

3.3.2 **The Cockling in relation with the Waviness**

Paper exhibits hydrophilic properties [34]. In the manufacturing process, huge increases of moisture content during the pre-drying process of paper causes the expansion of the fibres while the post-drying process causes the contraction of these fibres. The non-uniform expansion and contraction phenomenon creates out-of-plane surface irregularities [31][35][36][37].
Fig 7 (c) shows the cockling as one of the irregularity components on the paper surface. During the manufacturing and printing processes significant cockling can occur in thin papers whereas it has less affect on thick papers. Cockling is usually irregularly distributed on the surface and also depends on the local fibre orientation [37]. Waviness, on the other hand, is the result of an almost uniform distribution pattern usually caused by vibration, chatter, heat treatment, wrapping strains [6] and inappropriate tensions on the paper web.

Cockling and waviness are easily observable when paper is out of the machine web. Waviness is described as having lower frequency deformations of the paper surface as compared to that for cockling. Cockling is usually overlaid on the waves of waviness. Niskanen [38] describes cockling as 5 to 50 mm diameter, in-plane random deformations, with out-of-plane deviations of about 1 mm.

Figure (a) is the real surface. Figure (b) to (d) represents the component extracted from real surface (a) in order to explain relationship between waviness, cockling and roughness.

Fig 8 Separation of Fibre-roughness, Fibre-network roughness, Cockling and Waviness in the wavelength domain spectrum.
3.3.3 **Form, Position-error and Flaw**

Form is one of the topography components that represent the shape of the sample under test. It is related to curl, curve and spherical surfaces. Form is defined as the surface geometry which is superimposed in the topography. It is related to three dimensional (3-D) measurement systems and provides data to calculate the radius of curvature, surface angles and polynomial surfaces. Form-error study falls outside the scope of this thesis as the 3-D online spherical-surfaces measurements techniques are not being considered. However, details for a number of Form characterization and related algorithms selection techniques can be found in the article of Jung et al. [39].

While, the Position-error could develop due to the misalignment of the paper samples, in the laboratory measurements, and due to the insecure clamping or the incorrect positioning of the device, in the online setup. Typical examples of Position-error are out-of-flatness and out-of-roundness [30].

The flaw or surface defect is the most unwanted element which can easily ruin the production. The defects can appear on the surface due to the process material, process machines or any random abnormalities. Generally defects on the paper surface can develop during calendaring, coating, scratching caused by a blade cut or by foreign elements introduced during the manufacturing process. The original paper surface in Fig 9 has a defect mark which is represented as a high frequency abnormality in the original and roughness profiles.

**Fig 9** (a) Original profile of a rough surface. (b) - (d) depicts the relationship for the, waviness, roughness and form error components extracted from original. Length of the scanned line is on the horizontal axis and the height of the profile is on the vertical axis.
3.4 **BASIC SURFACE HEIGHT DEVIATION MEASUREMENT TECHNIQUE**

The basic principle of surface height measurements using a line of light is shown in Fig 10. The incident line of light falls on the single step height surface sample with incident angle α. The surface height deviation is ∆Z and ∆X is the displacement caused by the incident light due to the height differences.

![Diagram of surface height deviation](image)

**Fig 10** Simple setup for optical line of light projection to find out height deviations.

Where
- α = Line-of-light angle of incidence
- ∆Z = height variation to be calculated
- ∆X = Incidence line displacement due to deviation of surface height

The height variation ∆Z can be determined by applying simple trigonometry on the right triangle ABC in Fig 10.

\[
\tan(\alpha) = \frac{\Delta X}{\Delta Z}
\]

\[
\Delta Z = \Delta X \cdot \cot \alpha \tag{1}
\]
4 CHALLENGES, MOTIVATION AND RELATED RESEARCH

4.1 THE CHALLENGES TO DEVELOP ONLINE TOPOGRAPHY INSTRUMENT

It was discussed in the previous chapter that the conventional laboratory measurement is not sufficient and there has been a requirement for online surface measurements. The online measurement, however, is critical and challenging in both paper and paperboard manufacturing [16][40]. The paper web moves at high velocity and, at these velocities, the moving web introduces irrelevant data, for example, vibrations, stress on the surface, displacement, noise etc. These irrelevant data also embed in the real measurements making it difficult to measure the actual surface topography [18].

The paper machine speed can achieve 2000 m/min or higher and an online device should be capable of taking measurements in this range of operating speed. Furthermore, the resolution of the online device should be sufficiently high to distinguish individual wood fibres on the moving web. Thus the accuracy of online devices is essentially a challenge. Koshy et al. 2011 [41] suggest that, at present, the mechanical stylus or optical instruments are predominant in the laboratory and that it is difficult to apply these techniques for on-line process applications.

The online topographical technique is not common [2] and the techniques involving the use of a camera are also relatively new [42]. The available online equipment either has limited features or only detects surface fault as is also the concern in the majority of the continuous process industries [13][43][44]. In general online instrument should have strict compliance of robustness, precision, efficient, fast algorithm and stable operation [45], during full range of mill operating speeds.

4.2 THE MOTIVATION

The main motivation behind the research was in relation to considerations regarding the application and advantages of online topography within the industries. The long interest in online device by industries, SCA Paper Mill Ortviken and Iggesund Paperboard Iggesund, in Sweden encouraged Mid Sweden University researchers to accept this challenge. The new emerging techniques in the measurements field have made improvements to the overall quality of the products and have simultaneously tightened the performance criteria in the rapidly changing global market.

Fast computational speeds in addition to new computer based processing methods and advanced graphical interface software have already played an important role in the development of artificial-vision and machine visions systems. Many repetitive laboratory works, ranging from quality to quantitative assessments and inspections, have been replaced by automated systems. Such previous developments have led to this prototype version being developed.
4.3 The related research

Many laboratories based optical methods used to measure the surface, for example, by interferometric techniques, laser triangulation techniques and confocal microscopy techniques which measure the topography of a surface with precision [22]. Currently research is continuing into the offline techniques but the main focus is online measurements. For example, Hansson and Johansson [28] in 2000 developed a photometric stereo technique which was implemented by Åslund [34] in 2004 to make a fast surface measurement setup. Barros and Johansson [9] in 2005 designed a laboratory profilometer called the ‘Optitopo’ for paper surface roughness measurements which was also based on the photometric stereo principal.

The following are some related research activities.

i) Online measurement study in relation to paper coating surface morphology and paper optical properties using near-field scanning optical microscope (NSOM) [46].

ii) Online measurements in a press room to analyze the properties of paper print in relation to the press interactions [47].

iii) Method based on high frequency airborne ultrasound to measure the paper surface roughness was studied [48]. The principle was to measure attenuated ultrasound wave when it is reflected from a rough surface.

iv) An online roughness measurement method suggested based on non-contact pneumatic system [41].

v) Another new method was studied utilizing Friction Noise technique [17].

vi) A laser holographic interferometer has been developed which enables online surface measurement for machined work pieces [10].
5  OPTICAL ONLINE MEASUREMENT TECHNIQUES

The non-contact online optical topography measurement is emerging research and new measurement techniques are being explored. In the majority of the instruments, the target surface is illuminated either as a pulse or as a constant light source. The reflected light from the surface is captured by a detector (usually CCD camera). Various illumination techniques for example point, line and area are being used for online optical measurements. These techniques are discussed in the following sub sections.

5.1  POINT MEASUREMENT TECHNIQUE

There are some online devices that measure the surface topography point by point. The paper surface is illuminated by the point light source and the reflected light is measured by the detector. Fig 11 describes the basic setup for the point measurements in real time. This kind of technique usually employed for measurement along the machine direction.

5.2  LINE MEASUREMENT TECHNIQUE

In line of light projection technique, as contrast to the point projection, a beam of light, usually laser light, is shaped into a thin line and projected on the paper surface. Usually it is implemented for the measurement in the cross direction (CD) thus making the possibility for the measurement of the whole width of the paper web.

The laser line of light projection technique has been recently utilized by Xu and Yang and they have implemented a new algorithm to detect the surface defects of hot rolled strips online [49]. The setup consists of multiple cameras and two laser sources to illuminate the surface along the cross direction as shown in Fig 12.

5.3  AREA MEASUREMENT TECHNIQUE

In this method, an area of the target surface is illuminated and reflected light is acquired as the area image. This technique is usually used to measure rough surfaces and generally to detect the defects covering a wide area on the paper web. Fig 13 shows the setup of online “Metso Process and Quality Vision (Metso PQV)” developed by Metso Automation which was designed to detect the surface flaw and abnormalities. A beam of green colour LED causes the area illumination on the paper web along the cross direction and multiple cameras capture the reflected area.
Fig 11  Simple setup for online point measurements techniques.

Fig 12  Demonstration of line of light projection technique using two laser sources and multiple of cameras [49].

Fig 13  Example of online area scans measurement setup in paper industry. A wide area is covered on the moving paper web by multiple cameras to detect the paper surface defects, courtesy Metso Automation, Tampere, Finland.
5.4 Recently developed Online optical toography Instruments

In chapter 3 the research works in relation to the online measurements was described. Commercially, a few optical online instruments are available as described below;

i) Precision FotoSurf, developed by Honeywell, measures surface topography by taking images of the moving web. It can measure up to 15mm x 15mm surface topography.

ii) “Metso Process and Quality Vision (Metso PQV)” from Metso Corporation designed to detect online surface defects on the moving paper web.

iii) The Scantron “Proscan MastertrakI” is also a non-contact optical online profilometer with a single measurement sensor which continuously measures the surface profile in real time.

iv) “OnTop” the prototype non-contact optical surface topography instrument based on line of light triangulation technique is developed by the researchers at Mid Sweden University, Sweden.
6 SURFACE TOPOGRAPHY ANALYSIS

From chapter 3 surface topography, profiles and their components were known. There are two methods in practice to calculate the surface height in both industries and laboratories. One is statistical analysis and other is analysis in a wavelength spectrum.

6.1 STATISTICAL ANALYSIS OF SURFACE PROFILE

The statistical data contains an estimation of the overall surface irregularities in one simple variable such as Ra or Rq. Ra is the arithmetic average of the surface irregularities and Rq is the root mean square roughness. Ra and Rq are the functions of the profile deviations from a mean line [48] see Eq [2] and [3]. Fig 14 is a plot of a profile while the Ra and Rq levels are shown in order to observe the differences between them. In this case, ‘L’ is the total length scanned on the horizontal axis and ‘x’ is a reference mean line over which the topographical heights are measured. The surface profile height ‘Z’ is calculated with reference to the mean line and plotted on the vertical axis. The widely used Ra and Rq formulas are represented in the spatial domain as;

![Fig 14 Average levels of roughness Ra and rms roughness Rq of a typical profile extracted from one of our samples.](image)

Arithmetic Average Roughness=
$$Ra = \frac{1}{L} \sum_{x=0}^{L-1} (Z_x - \bar{Z})$$ \hspace{1cm} (2)

Root mean square Roughness (rms)=
$$Rq = \sqrt{\frac{1}{L} \sum_{x=0}^{L-1} (Z_x - \bar{Z})^2}$$ \hspace{1cm} (3)

where $\bar{Z}$ is Mean line $= \frac{1}{L} \sum_{x=0}^{L-1} Z_x$

Ra and Rq are widely used terms. These are the functions of profile deviations from a mean line, calculated in order to extract the surface quality as a quantitative analysis [50][51][52][53]. In Eq 3 it can be seen that the height amplitudes are
squared, therefore, the rms is more sensitive to the peaks and valleys in the profile. For most of the samples, studied in this work, the amplitudes of $R_q$ were found to be about 10-11% higher than the $R_a$ and all the results presented here are in terms of rms $R_q$.

6.1.1 The Profile Filter and Wavelength Cut-off Selection

To separate the topography components such as roughness, waviness and position-error from the measured profile, appropriate filters are required. In the line of light measurement technique the position-error, for example, profile curve or tilt are generally removed by applying an appropriate fit line or a fit curve algorithm as one of the pre-processing steps.

Roughness is obtained by applying a high pass filter with an appropriate long-wavelength cut-off $\lambda_c$. The long-wavelength cut-off $\lambda_c$ value defines how much fine roughness is needed to be measured.

The effect of a long-wavelength cut-off $\lambda_c$ on the measurement of the roughness is plotted in Fig 15, where the profile evaluation length $L$ is 70 mm. In this example the affect on the roughness is shown by applying four different $\lambda_c$. The longest value of $\lambda_c$ was 1.7 mm and the shortest was 0.17 mm resulting in roughness $R_q$ of 14.1 $\mu$m and 3.4 $\mu$m respectively. A carefully chosen $\lambda_c$ can extract the roughness of the range of interest.

Fig 15 Affect of various long-wavelength cut-off on the measurement of roughness $R_q$.

6.2 ANALYSIS OF SURFACE PROFILE IN WAVELENGTH SPECTRA

In reality, the surface geometry of the paper contains a large amount of information that is not commonly being evaluated. For example, in the case of
For online measurements, the paper surface on the moving web can have a number of runtime irregularities in addition to roughness waviness, tension affects, curl and cockling etc. Therefore the value of Ra and Rq could easily be dominated by one or more such irregularities leading to inaccurate results.

It has been seen in the above section that the statistical result contains an estimation of the surface irregularities in one variable which greatly depends on the long-wavelength cut-off values. Analysis in Ra, Rq can easily distinguish those surfaces where the differences of topography between the samples are large but it is difficult if the differences are narrow. Thus a measurement in a single value is inadequate if a detailed surface characterization is required. In contrast to this, an analysis in the wavelength spectrum can provide comprehensively information of the irregularities for each of the wavelength components. It will enable different grades of samples to be classified including those where the differences are very minor.

6.2.1 Power spectral calculations

The surface profiles measured in the time domain are transformed to the frequency domain, by applying a Fourier Transform, for spectral analysis.

If \( h(w) \) is the spatial input topography profile in the time domain then the Fourier transform \( F \) of the input signal returns the frequency spectrum \( Z(f) \) in the frequency domain.

\[
Z(f) = F \{h(w)\} \quad (4)
\]

\( Z(f) \) being a complex number, contains both real and imaginary frequency components. To find power at each frequency, the power spectrum is calculated as a product of the frequency spectrum \( Z(f) \) and the complex conjugate of \( Z(f) \). Hence, the power spectrum \( S(f) \) is defined as the power of the input signal per unit frequency and is mathematically represented as:

\[
S(f) = Z(f) \cdot \bar{Z}(f) = |Z(f)|^2 \quad (5)
\]

Where, \( \bar{Z}(f) \) is the complex conjugate of \( Z(f) \)

Thus in the case of more than one profile, there will be more than one power spectra \( S(f) \). In such cases usually the average of all spectra is determined. The averaged power spectrum \( S(f) \), a function of frequency \( f \), is further converted to \( S(\lambda) \) as a function of wavelength \( \lambda \), where \( \lambda \) is defined as:

\[
\lambda = 1/f \quad (6)
\]

The wavelength power spectrum \( S(\lambda) \) usually contains a large number of wavelength components especially if the resolution is high, as it would then be
difficult to analyze and plot. Therefore, the spectrum is divided into ranges of wavelength bands.

6.2.2 Example of Spectral Plot

One of the spectral plot examples from newspaper samples is shown in Fig 16. Here the topography irregularities can be analyzed in each component of the wavelength in a range 0.1 mm to 23 mm. Thus features of the surface can be analyzed in each component of the wavelength which is not possible if the measurements had been taken in a single value of Ra or Rq. Paper surface features such as fibre-roughness, fibre-network (fibre bundles etc.) roughness, cockling, waviness and form error can be determined as per their corresponding wavelength ranges.

Fig 16 Example of spectral plot which shows the features of the surface height in each wavelength components from 0.1 to 23 mm range.

6.2.3 Relative percent difference Analysis

The data in the wavelength spectrum could be huge depending upon the resolution of the scanning line. For example, if 70 mm length is to be scanned on the paper surface, then the line profile will contain 70,000 points if the resolution of the profilometer is 1 µm. This profile, if transformed into a frequency domain, will contain 30,000 spatial wavelength components. In such cases, it will become difficult to distinguish between two similar grades of samples. Fig 17(a) is the example of two spectral plots where the topography difference between them is very small. This plot shows that the differences between the two is very subtle, but is noticeable.
Fig 17  Topography comparison of two samples, in wavelength spectra, in (a) is difficult to see the differences between the two. Relative Percent Difference between these two plots is shown in (b) where the differences between the two samples can easily be seen in the full wavelength scale.

To evaluate and study the differences between the same grades of samples the Relative Percent Difference calculation method has been adopted in this thesis. For example the relative percent difference of the two Plots in Fig 17(a) namely Plot1 (P1) and Plot2 (P2) can be calculated as,

The Relative Percent Difference in P1 and P2

\[
=\left[\frac{(S(\lambda)_{P1} - S(\lambda)_{P2})}{S(\lambda)_{P1}}\right] \times 100
\]

Where

\( S(\lambda)_{P1} = \text{variance of height in the P1.} \)
\( S(\lambda)_{P2} = \text{variance of height in the P2.} \)

The difference between the two is plotted in Fig 17(b). This plot is quite clear and the differences between the two topographies can now be seen very clearly along the full wavelength spectra.
7 AN INVESTIGATION: TOPOGRAPHY DIFFERENCES IN CD AND MD

Paper topography in a laboratory is measured either in the CD or in the MD or both as shown in Fig 18. The online topography, generally can be performed in one direction, therefore, a selection of the measurement direction in an online machine is important. A separate laboratory investigation was carried out in order to determine which direction would be best for the online topography of paper and paperboard. This chapter investigates and presents the results to determine any differences in the CD and MD.

![Online surface topography can be scanned either in MD (left) or in CD (right).](image)

7.1 PAPER SURFACE PROPERTIES

Paper is made of pulp fibre which posses anisotropic properties [54][55]. Generally during a paper manufacturing process, the majority of the fibres are elongated in the machine direction whereas there are fewer in the cross direction. Paper is a hydrophilic material and moisture and coating causes changes in the paper dimension thus affecting the surface topography mainly in the cross direction.

In-plane fibre orientation measurement can be obtained as shown in Fig 19 [56]. The figure contains two coordinate plots. One is the global coordinate (CD, MD) and other is the local coordinate (n1, n2). In the local coordinate system n1 is the axis in which the maximum fibre elongation occurred while n2 is for the minimum elongation axis. The orientation angle θ is the angle between the MD and the direction n1. The anisotropy is defined as the ratio of two elongation distances ‘a’ and ‘b’ which shows how strong the fibre moves its direction:

$$\xi = a/b$$

Leppänen and Hämäläinen [56] made a study on a number of sample papers and found that the fibre elongation in the MD is higher than in the CD.
The intensity of anisotropy is defined as $\xi = a/[56]$.

### 7.1.1 Sample Details

The investigation study was conducted on 20 paper samples, each 60 by 60 mm in size. The 20 samples were divided into 4 groups according to their surface qualities. The samples are listed in Table 1.

<table>
<thead>
<tr>
<th>Sample Groups</th>
<th>Description</th>
<th>Surface</th>
<th>No. of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Paperboard</td>
<td>Uncoated</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Newspaper</td>
<td>Uncoated</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>LWC</td>
<td>Coated</td>
<td>5</td>
</tr>
<tr>
<td>4(a)</td>
<td>Paperboard</td>
<td>Coated</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>(edge web)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4(b)</td>
<td>Paperboard</td>
<td>Coated</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>(Middle web)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The paperboard samples were provided by Iggesund Paperboard AB, Iggesund, Sweden whereas the newspaper and LWC samples were provided by SCA Ortviken AB, Sundsvall, Sweden. Samples include the coated and uncoated sides of paper and paperboards which covers a wide range of topography differences. The samples in group 4(a) are those taken from the edge of the paperboard web while the samples in 4(b) were taken from the middle. It is commonly known that the topography is almost the same for the edge and middle position of the reel but it is also generally known that the topography level could be higher at the edge position due to shrinkage during the production steps. The samples cover the wide range of surface grades of paper including the edge and the middle of the reel which ensures that this investigation also contains the results of the same family grades.
7.1.2 FRT Profilometer and Sample Measurement

The lab measurements for the samples listed in Table 1 were obtained from FRT MicroProf® (Fries Research & Technology GmbH) profilometer. The profilometer is equipped with a CCD optical sensor and scanning mechanism. It has a maximum resolution of 1 µm in the x and y directions and 10 nm in the z-direction. However, the measurements in this study were taken when the resolution was set to 10 µm in the x and y directions. Each sample is scanned in raster fashion both in the CD and MD separately. Fig 20 shows how each sample is scanned in a matrix of 6000 by 100 pixels. Each horizontal line makes one line profile. The distance between the individual measured points was 10 µm and 6000 points were scanned horizontally resulting in a total length of line that is 60 mm. Such 100 line profiles were created by scanning vertically down with an equal spacing of 0.6 mm. Hence the physical area of the paper surface covered in the measurement was 60 by 60 mm.

![Image showing the measurement setup]

Fig 20 Sample measurement resolution along horizontal axis was 10 µm so total 6000 measurements made to scan 60 mm along horizontal axis. Such 100 line profiles were created along vertical axis with resolution of 0.6 mm in order to cover the whole sample.

7.1.3 Processing of the line profiles

The analysis method adopted in this study is presented in the flow chart in Fig 21. Each sample contains 100 profiles for CD and 100 for MD. These time domain profiles are denoted as h(w) which was transformed into the frequency domain function Z(f) by applying a Fourier Transform. The power spectra were calculated in the function S(f). Later on the S(f) is also converted into the wavelength spectra as S(λ). Finally the average was calculated for every 100 spectra. These average spectra represent the topography of each individual sample in the CD and in the MD. The comparison of the CD and MD average spectra were performed and plotted in the result.
7.2 Topography Characterization in CD and MD

Fig 22 shows the surface topography plots in wavelength bands for all the 20 samples. The plot classifies and clearly distinguishes between the four different groups of papers, uncoated paperboard, uncoated newspaper, LWC and coated paperboard. The roughest surface is for the uncoated paperboard (group 1) which has the highest variance amplitudes in relation to the irregularities on the surface. The smoothest surface was found for the coated paperboard (group 4) having the minimum surface irregularities.
Fig 22 Surface characterization and comparison of 20 samples. The characterization correlates with the quality grades of the samples as listed in Table 1. Fig (a) is spectral plots for CD and (b) for MD.
7.3 **Relative Percent Differences Between CD and MD**

The topographical analysis of the 20 samples was achieved in relative percent differences according to Eq 7 followed by the group wise analysis results in the subsequent sections.

The Relative Percent Difference in CD vs. MD

\[
\text{Relative Percent Difference} = \left( \frac{S(\lambda)_{CD} - S(\lambda)_{MD}}{S(\lambda)_{CD}} \right) \times 100
\]

(9)

Where

\( S(\lambda)_{CD} \) = variance of height in the CD.

\( S(\lambda)_{MD} \) = variance of height in the MD.

### 7.3.1 Uncoated Paperboards

The relative percent differences in the CD and MD for the uncoated paperboards is presented in Fig 23. This plot clearly distinguishes between the measurements in both the directions. It can be noted that from the wavelength 20 µm to 500 µm, the CD measurements always have a higher value (about 15%) in relation to the surface topography as compared to that for the MD. On the other hand, from 700 µm to 8 mm the trend average shows that MD measurements are providing higher surface topographical values than those for the CD.

![Graph](FIG23.png)

Fig 23 The Relative percent difference in the CD and the MD for uncoated paperboard samples.

### 7.3.2 Newspaper samples

The CD MD relative percent difference plots of the newspaper samples are presented in Fig 24. It can be stated, roughly, that for such kind of papers the CD measurements yield higher topographical amplitudes than those of the MD within the range 20 µm to 4 mm with some exception from 800 µm to 950 µm. However, beyond 4 mm the measurement results are fluctuating and unclear.
7.3.3 Lightweight Coated paper (LWC)

Fig 25 characterizes the LWC paper samples. These paper samples show the topography which is almost similar to those of the newspaper samples.

7.3.4 Coated Paperboard

The coated paperboard consists of samples from the edge web and from the middle web as mentioned in Table 1. Fig 26 is a relative percent difference plot for the edge paperboard samples, where the shrinkage in the CD is large. From 20 µm to 1 mm (with exception from 90 to 110 µm) the level of topography in the CD is considerably larger (about 15-20%) than the MD. In contrast to this in Fig 27 the relative percent difference for the middle web samples, from 20 to 90 µm, seems very close to zero. However, for the middle web samples a few valleys and peaks beyond the wavelength of 500 µm can also be observed.
The close similarities were found in the shorter wavelength range 20 µm to 500 µm among the uncoated paperboards, uncoated newspapers and LWC where the CD topography levels are higher than MD. Again the topographical similarities for these grades of papers and paperboards started with a dip in the MD from 500 µm wavelength. For the edge-web coated paperboards the higher topography in the CD were found in the shorter wavelength from 20 to 90 µm whereas for the samples of middle-web coated paperboards the relative percent difference in the CD and the MD is close to zero for shorter wavelength up to 90 µm. The dip for the majority of the measurements in the MD at the different wavelength ranges depends upon the paper quality grades and suggests an increase in the topography height in the MD for this specific wavelength band. This could be explained by the
fact that the wood fibres in the majority of cases align in the MD, and those fibres in the length direction could influence these wavelengths, which will have a particular effect on the measurements of the uncoated surfaces.

The results vary between paper and paperboard qualities. It suggests that this type of investigation is required to be performed on each specific paper and paperboard quality before any decision is taken to make measurements (especially online) in either the CD or the MD. These types of measurements can also contribute to estimate the tendency of the fibre orientation along the CD and the MD.

The result indicates that there are substantial differences in the CD and the MD topography amplitudes. Therefore, measurements in both the CD and the MD could prove to be beneficial in characterizing the surface quality of a sample. This, however, can be difficult to achieve in an online situation because of the high velocities of the paper webs and the large amount of data that would have to be gathered and processed in real-time.

The overall conclusion is that the results confirm that the surface topography amplitudes are higher in the CD for most of the shorter spatial wavelength for the samples of newspapers, light weight coated paper (LWC) and paperboards. Because the manufacturer of these grades of papers and paperboards are interested in obtaining accurate topographical measurements in the shorter wavelength, therefore, it was meaningful to design a prototype that can measure the online paper web topography in the cross direction rather than in the machine direction.
8 DEVELOPMENT OF ONLINE INSTRUMENT THE ONTOP

The major limitations and disadvantages of laboratory based quality inspection in the production industries have been discussed in chapter 2 and in chapter 5 the optical measurement research activities have been covered. In reality the available online devices are in the phase of further development mainly to minimize their limitations and improve accuracy. The common limitation for online devices is that majority of the methods work in a satisfactory manner in those cases where the differences in the topography of the surfaces are large but difficulties do arise in the evaluation of paper surfaces which have very small topographical differences [57]. Furthermore, some techniques target a very limited surface area and thus there remains the requirement for a topography measurement method which can measure a wide range of surface.

OnTop is an online topography prototype instrument, designed to measure the paper web length up to 210 mm along the CD, thus it covers a wide range of surface irregularities. It has been developed based on the line of light illumination technique. According to ASME B46.1-2002 [30] standards the prototype lies in the category of ‘Type II Full Profiling non-contact instruments.

The prototype has been tested up to the maximum operating speeds of paperboard machine that is up to 800 m/min. Online analysis techniques have successfully characterized the paper and paperboard surface. In the trial tests, the prototype has executed 6 measurements in one second. Each measurement cycle includes image acquisition, image processing steps, data analysis, data saving and the display of results in the Ra, Rq and as wavelength spectra. Therefore, the prototype has successfully taken online measurements for the whole web meter by meter.

This chapter provides the information regarding the performance and accuracy of the developed prototype, the OnTop, by correlating offline and online measurements.

8.1.1 The fast measurement technique

It was previously mentioned that the majority of the laboratory optical profilometers scan a sample point by point [58] to create a vector of line profile. In contrast to this, this prototype is designed on a line of light projection technique thus a vector of line-profile is obtained in a single step which made for a very fast acquisition of the entire line. In order to obtain an accurate and stable measurement system, the aim was for a robust prototype assembly with a fast algorithm as these are among the criteria for on-line production devices [43]. Fig 28 shows prototype and line projection setup in the CD.
8.2 **Offline verifications of the OnTop**

A step height accuracy was verified by a specimen of a height of 75 µm and examined by a Mahr digital height indicator model-1083 and by the OnTop. The specimen image and the profile are shown in Fig 30 (left).

The Fig 29 (right) is the plot of a paperboard sample in the wavelength spectra built up by the OnTop and by the FRT profilometer. The two spectral plots almost correlate with respect to the height amplitude in the corresponding wavelength. The amplitude is mismatched in the longer wavelength, which could be the fact that lab instrument uses vacuum table to hold the sample, thus reducing the amplitude in the longer wavelength.
8.3 ONLINE MEASUREMENTS VERSUS OFFLINE MEASUREMENTS

Further performance and accuracy evaluation of the prototype were achieved by correlating the online measurements with the offline measurements. Eight sample reels of paperboard and another eight sample reels of newspaper were measured by the online prototype the OnTop and by the industrial Sture-3 laboratory profilometer (from MoRe research AB, Sweden). The correlation among each individual measurement in the rms roughness $R_q$ is plotted in Fig 30.

![Figure 30](image)

Fig 30 Correlation between on-line and off-line roughness $R_q$ measured by i) Offline Sture Industrial laboratory profilometer and ii) Online topography device the OnTop. Fig (a) is the correlation for 8 reels of paperboard and (b) is the correlation for 8 reels of newspaper.

8.3.1 OnTop: hardware and processing technique

The hardware for the prototype consists of pulsed laser sources, two plano-convex cylindrical lenses, CCD sensors, trigger pulsed generator and dc power sources. The beam of the laser is transformed into a sharp thin line using cylindrical lenses and is projected onto the surface of the paper web. The low-specular reflected line of light from the paper surface, which carries the surface topographical information, is captured by multiple cameras.

Image processing techniques performed include, fast acquisition of images synchronized with the pulsed laser sources, pre-processing and post-processing filters, cropping the area of interest, line profile processing algorithm, transformation from the time domain to the frequency domain. Finally after averaging the multiple measurements the quantitative results in the form of $R_a$, $R_q$ and wavelength spectra are recorded and displayed.
8.4 **SYSTEM NOISE, RESOLUTION AND ACCURACY**

The accuracy of the overall system can deteriorate due to the noise in the electronics system, imaging sensor, and speckle in the laser line. The average noise based on Rq was found to be 8.1 nm (4.3%). The noise was calculated when the long-wavelength cutoff $\lambda_c$ was 8.75 mm. The imaging sensor occupies 1600 pixels in order to capture a 70 mm physical length (evaluation length) on the paper surface. The smallest unit is one pixel, therefore, the spatial resolution is 43.75 $\mu$m.

8.5 **DISCUSSION AND CONCLUSIONS**

The plots in Fig 30 shows a reasonable correlation and harmony among the results obtained from the on-line and off-line devices which supports the overall online results. However, some differences between on-line and off-line can be explained as being due to the fact that the on-line measurements are the average data of the whole reel whereas the off-line are only the average of three small pieces of samples taken from the reels. It can be seen that the measurements of newspaper reels show less correlation than the paperboards reels. It could be due to the fact that the online device measures the roughness under the condition in which the web is stretched, while the offline device measures when the sample is in a free hanging status. In the free hanging status, the longer wavelength components, for example cockling and waviness, can exist at a higher value. Thus under these two different measurement conditions the less correlation is observed in the case of newspaper reels. In these plots, the R-Squared is a statistical measure of how close the match is to the real data in relation the regression line. In the case of paperboards in Fig 30 (a) the 0.9684 value of R-Squared approximates that the linear regression between the real and predicted line is 96.84%.
9 ONLINE SURFACE CHARACTERIZATION IN RMS ROUGHNESS

The main essence of this thesis is the online characterization of paper web surface. The importance and motivation for the online device was described in chapter 4. The developed prototype the OnTop was used in the online measurement and analysis of the newspapers and paperboards surface topography in the Pilot Coating Plant at Iggesund in Sweden. The prototype measures the entire reels, meter by meter and classifies the whole reel in traditional units of roughness Rq. The online measurements have successfully characterized and distinguished all the 16 different grades of newspaper and paperboard reels including the reels having the same family of quality grades.

9.1 SAMPLE REELS DESCRIPTION

A total 8 sample reels, including 4 newspaper and 4 paperboard, were examined online and are listed in Table 2. The sample consists of different grades and weights of newspaper and paperboard reels. Each of the newspaper reels were measured in relation to their wireside and topside surfaces, separately, and similarly the paperboard reels were also measured for the uncoated and coated sides of the surfaces.

The paperboard reels were provided by Iggesund Paperboard AB, Iggesund, Sweden and the newspaper reels by SCA Ortviken AB, Sundsvall, Sweden.

<table>
<thead>
<tr>
<th>Reel. No.</th>
<th>Description</th>
<th>Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>43 gsm Newspaper</td>
<td>Topside</td>
</tr>
<tr>
<td>R1</td>
<td>43 gsm Newspaper</td>
<td>Wireside</td>
</tr>
<tr>
<td>R2</td>
<td>49 gsm Newspaper</td>
<td>Topside</td>
</tr>
<tr>
<td>R2</td>
<td>49 gsm Newspaper</td>
<td>Wireside</td>
</tr>
<tr>
<td>R3</td>
<td>51 gsm Newspaper</td>
<td>Topside</td>
</tr>
<tr>
<td>R3</td>
<td>51 gsm Newspaper</td>
<td>Wireside</td>
</tr>
<tr>
<td>R4</td>
<td>60 gsm Newspaper</td>
<td>Topside</td>
</tr>
<tr>
<td>R4</td>
<td>60 gsm Newspaper</td>
<td>Wireside</td>
</tr>
<tr>
<td>R5</td>
<td>Edge position paperboard</td>
<td></td>
</tr>
<tr>
<td>R5</td>
<td>20 gsm Edge-position paperboard</td>
<td>Coated</td>
</tr>
<tr>
<td>R6</td>
<td>Middle-position paperboard</td>
<td>Uncoated</td>
</tr>
<tr>
<td>R6</td>
<td>20 gsm middle-position paperboard</td>
<td>Coated</td>
</tr>
<tr>
<td>R7</td>
<td>Edge-position paperboard</td>
<td>Uncoated</td>
</tr>
<tr>
<td>R7</td>
<td>24 gsm Edge-position paperboard</td>
<td>Coated</td>
</tr>
<tr>
<td>R8</td>
<td>Middle-position paperboard</td>
<td>Uncoated</td>
</tr>
<tr>
<td>R8</td>
<td>24 gsm Middle-position paperboard</td>
<td>Coated</td>
</tr>
</tbody>
</table>
9.2 3-D SURFACE MAP OF AN ENTIRE REEL

3-D surface map of one of the newspaper reels constructed by OnTop is shown in Fig 31. Here on the y-axis the width of the paper surface in cross direction is 70 mm, on the x-axis the number of lines scanned in machine direction is 3000 and the surface profile height is plotted on the z-axis in µm. Each line was scanned along the MD at a distance of 1.66 meter, which means a total length of 4,980 meters of the reel was measured. The measurements throughout the reel were found in logical harmony. The average Rq for the entire measurement was 3.038 µm with peak to peak variations of about 2.95 to 3.15 µm.

The 3D surface map of an entire reel would prove to be helpful together with the values such as average roughness, rms roughness, peak-peak variations, etc in order to be able to deduce the quality of the whole reel surface. In addition to this, if the surface contains defect it will be noticeable on the 3D map along with its location, especially if the defect appears in the MD.

![Fig 31](image.png) A typical example of one of the newspaper reels plotted as 3-D profile-map. On z-axis height of the surface irregularities in µm, on y-axis the width of the surface measured in CD and on x-axis the total number of measurements as well as length of the measured reel are shown.

9.3 CLASSIFICATION OF NEWSPAPER REELS

Fig 32 shows the surface roughness plots for the 4 newspaper reels in real time. The legend of each plot also contains the average roughness Rq for the entire measurements. Fig 32(a) is for reels having a grammage of 43 and 49 gsm while Fig 32(b) is for 51 and 60 gsm reels. In these figures the roughness levels are found to be higher on the wireside as compared to the topside surface except for the 43 gsm reels. In the 43 gsm reel, the topography levels measured for the topside proved to be higher than for the wireside and this measurement was also found in agreement with the roughness data for the newspaper manufacturer.

In Fig 32(a) the 49 gsm reel is found to have a higher roughness than the 43 gsm reel and in Fig 32(b) the surface roughness levels are found higher for the 60 gsm as compared to those for the 51 gsm reels. The classification of the newspaper sample reels starting from the finest to the roughest surface is listed in Table 3.
Fig 32 On-line roughness comparisons among the newspaper sample reels of grammage 43, 49, 51 and 60 gsm. Here each measurement has been taken at every 1.66 meter steps.

<table>
<thead>
<tr>
<th>Reel Number</th>
<th>Description</th>
<th>Surface</th>
<th>$R_q$ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R3</td>
<td>51 gsm, Newspaper</td>
<td>Top side</td>
<td>3.032</td>
</tr>
<tr>
<td>R1</td>
<td>43 gsm, Newspaper</td>
<td>Wire side</td>
<td>3.038</td>
</tr>
<tr>
<td>R3</td>
<td>51 gsm, Newspaper</td>
<td>Wire side</td>
<td>3.172</td>
</tr>
<tr>
<td>R1</td>
<td>43 gsm, Newspaper</td>
<td>Top side</td>
<td>3.231</td>
</tr>
<tr>
<td>R4</td>
<td>60 gsm, Newspaper</td>
<td>Top side</td>
<td>3.345</td>
</tr>
<tr>
<td>R4</td>
<td>60 gsm, Newspaper</td>
<td>Wire side</td>
<td>3.506</td>
</tr>
<tr>
<td>R2</td>
<td>49 gsm, Newspaper</td>
<td>Top side</td>
<td>4.523</td>
</tr>
<tr>
<td>R2</td>
<td>49 gsm, Newspaper</td>
<td>Wire side</td>
<td>5.480</td>
</tr>
</tbody>
</table>
9.4 CLASSIFICATION OF PAPERBOARD REELS

In a similar manner to the above figures the measurements on the 4 paperboard reels are plotted in Fig 33. In both Figs 33(a) and (b) the roughness amplitudes were found to be higher for the uncoated sides as compared to those for the coated sides, which is an obvious result. Figures (a) and (b) contain the important results in relation to the edge reels and the middle reels. It was already known that the topographical differences between the edge positions and the middle positions are normally very low but, at the same time, it is also accepted that the roughness on the edge reel is expected to be slightly higher. The same evidence is noted in the plots of the edge and the middle reels in figures (a) and (b) for both the coated and uncoated sides of the paperboard surfaces.

One more important result relating the coating weight with that of the roughness can be noted in these plots. It has been mentioned that during the manufacturing of reel 5 and 6 the level of coating applied to their surfaces were lower (20 gsm) than the level of coating applied to reel 7 and 8 (24 gsm). Hence the coated sides of reel 7 and 8 were expected to be smoother than those for reels 5 and 6 and this was determined by their respective plots. Table 4 classifies all the 4 paperboard sample reels starting from the finest surface.

![Graph](image_url)

*Fig 33  On-line roughness comparison for the paperboard reels. Both (a) and (b) have a total measurement length of 213 meters. Here, each measurement has been taken at every 1.11 meter steps.*
<table>
<thead>
<tr>
<th>Reel No.</th>
<th>Description</th>
<th>Surface</th>
<th>Rq (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R8</td>
<td>24 gsm Middle paperboard</td>
<td>Coated</td>
<td>1.78</td>
</tr>
<tr>
<td>R7</td>
<td>24 gsm Edge paperboard</td>
<td>Coated</td>
<td>1.89</td>
</tr>
<tr>
<td>R6</td>
<td>20 gsm Middle paperboard</td>
<td>Coated</td>
<td>1.94</td>
</tr>
<tr>
<td>R5</td>
<td>20 gsm Edge paperboard</td>
<td>Coated</td>
<td>2.00</td>
</tr>
<tr>
<td>R6</td>
<td>Middle paperboard</td>
<td>Uncoated</td>
<td>3.58</td>
</tr>
<tr>
<td>R8</td>
<td>Middle paperboard</td>
<td>Uncoated</td>
<td>3.70</td>
</tr>
<tr>
<td>R5</td>
<td>Edge paperboard</td>
<td>Uncoated</td>
<td>3.73</td>
</tr>
<tr>
<td>R7</td>
<td>Edge paperboard</td>
<td>Uncoated</td>
<td>3.98</td>
</tr>
</tbody>
</table>

9.5 CONCLUSIONS

The online measurements have clearly been able to distinguish between the different quality grades of newspaper and paperboard surfaces as follows,

i) Wiresside newspaper and topside newspaper reels.

ii) Base paperboard and coated paperboard reels.

iii) The edge position and the middle position paperboard reels.

iv) Coated paperboard with light coating (20 gsm) and with higher coating (24 gsm).

The results presented have achieved the micro level roughness classification among the samples with wide and narrow differences. The classifications of the samples having similar quality grades were also achieved as presented in Table 4.

It is possible to conclude from the results of the online trial tests shown that the prototype can differentiate between the surface qualities of different grades as well as for similar grades, making the method useful for the paper and paperboard industries.
In the previous chapter online measurements and classification of newspaper and paperboard were described in rms roughness $R_q$. The importance of the topography analysis in the wavelength spectra was emphasized in section 6.2 and it was described that for a detailed topographical analysis the single value of $R_q$ is inadequate. In this chapter online characterization in the wavelength spectra, ranging from 0.1 to 10 mm, for the same sample reels as described in Table 2 in chapter 9 is presented.

A number of spectra were obtained for each of the reels depending upon the number of measurements. For the sake of simplicity all the individual spectra were averaged to obtain the final spectrum. Therefore, each reel has been characterized by the final averaged spectrum in the following sections.

### 10.1 Characterization of Newspaper Reels

Fig 34 shows the online topography plots for the 4 newspaper reels of 43, 49, 51 and 60 gsm. The spectral plot is able to distinguish each reel throughout the full wavelength scale from 0.1 to 10 mm. Reel R2, 49 gsm (wireside) is detected as having the highest surface topography levels and reel R3, 51 gsm (topside) as having the lowest topography levels. Hence reel R2 has the roughest surface while reel R3 has the smoothest surface among all newspaper sample reels. Generally the topside is smoother than the wireside surface and the same has been measured in Fig 34 for all of the reels except the 43 gsm reel. In the 43 gsm, as already described in section 9.3, these results were also found in agreement with the roughness data of the newspaper manufacturer. The 4 newspaper sample reels were classified starting from the finest to the roughest surface in Table 5.

### 10.1.1 Characterization of Paperboard Reels

The paperboard samples include uncoated sides, coated sides, edge positions and middle positions reels. There are a total of 4 paperboard sample reels namely from R5 to R8. The first two reels R5 and R6 were manufactured in one machine and the last two R7 and R8 in another machine.

It is evident from the plots in Fig 35 that all the uncoated surface has higher topography levels than the coated surface which is an obvious result. It can be approximated that the uncoated edge position reel R7, shows the roughest surface while, the coated side middle reel R8, the smoothest surface.
Fig 34 Online topography measurements of 4 newspapers sample reels. Plots are the average spectrum for each sample reel from R1 to R4. The dashed plots are for wire side and solid plots are for top side surfaces.

Fig 35 Online topography measurements of 8 paperboards sample reels. Plots are the average spectral for each sample reel from reel R9 to R16. The dashed plots are for uncoated surface and solid plots are for coated surfaces.
Table 5 Classification of 4 Newspaper reels in sub-wavelength bands.

<table>
<thead>
<tr>
<th>Reel No.</th>
<th>Description</th>
<th>Surface</th>
<th>Rq Unit</th>
<th>Range of wavelength bands in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1-0.2</td>
</tr>
<tr>
<td>R3</td>
<td>51 gsm Newspaper</td>
<td>Topside</td>
<td>µm</td>
<td>1.503</td>
</tr>
<tr>
<td>R1</td>
<td>43 gsm Newspaper</td>
<td>Wireside</td>
<td>µm</td>
<td>1.553</td>
</tr>
<tr>
<td>R3</td>
<td>51 gsm Newspaper</td>
<td>Wireside</td>
<td>µm</td>
<td>1.505</td>
</tr>
<tr>
<td>R1</td>
<td>43 gsm Newspaper</td>
<td>Topside</td>
<td>µm</td>
<td>1.594</td>
</tr>
<tr>
<td>R4</td>
<td>60 gsm Newspaper</td>
<td>Topside</td>
<td>µm</td>
<td>1.498</td>
</tr>
<tr>
<td>R4</td>
<td>60 gsm Newspaper</td>
<td>Wireside</td>
<td>µm</td>
<td>1.463</td>
</tr>
<tr>
<td>R2</td>
<td>49 gsm Newspaper</td>
<td>Topside</td>
<td>µm</td>
<td>1.553</td>
</tr>
<tr>
<td>R2</td>
<td>49 gsm Newspaper</td>
<td>Wireside</td>
<td>µm</td>
<td>1.867</td>
</tr>
</tbody>
</table>

Table 6 Classification of 4 paperboard reels in sub-wavelength bands.

<table>
<thead>
<tr>
<th>Reel No.</th>
<th>Description</th>
<th>Surface</th>
<th>Rq Unit</th>
<th>Range of wavelength bands in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1-0.2</td>
</tr>
<tr>
<td>R8</td>
<td>Middle side (24 gsm)</td>
<td>Coated</td>
<td>µm</td>
<td>0.757</td>
</tr>
<tr>
<td>R7</td>
<td>Edge side (24 gsm)</td>
<td>Coated</td>
<td>µm</td>
<td>0.772</td>
</tr>
<tr>
<td>R6</td>
<td>Middle side (20 gsm)</td>
<td>Coated</td>
<td>µm</td>
<td>0.686</td>
</tr>
<tr>
<td>R5</td>
<td>Edge side (20 gsm)</td>
<td>Coated</td>
<td>µm</td>
<td>0.718</td>
</tr>
<tr>
<td>R8</td>
<td>Middle side</td>
<td>Uncoated</td>
<td>µm</td>
<td>1.504</td>
</tr>
<tr>
<td>R6</td>
<td>Middle side</td>
<td>Uncoated</td>
<td>µm</td>
<td>1.340</td>
</tr>
<tr>
<td>R5</td>
<td>Edge side</td>
<td>Uncoated</td>
<td>µm</td>
<td>1.291</td>
</tr>
<tr>
<td>R7</td>
<td>Edge side</td>
<td>Uncoated</td>
<td>µm</td>
<td>1.595</td>
</tr>
</tbody>
</table>

10.1.2 Topography comparison between Edge and Middle position reels

During manufacturing, the uniform smoothness across the full width of the paper web is required, therefore, it is necessary to measure the surface quality at both the edge and the middle positions of the paper web. In this section a comparison between the edge and the middle position reels is evaluated. The Relative Percent Difference between the Edge Reel vs. the Middle Reel is calculated as shown below,

\[
\text{Relative Percent Difference} = \left( \frac{\text{ER}_Amp - \text{MR}_Amp}{\text{ER}_Amp} \right) \times 100
\]

where

\[
\text{ER}_Amp = \text{Edge Reel topography amplitude.}
\]
\[
\text{MR}_Amp = \text{Middle Reel topography amplitude.}
\]

According to the above Eq 10 if the relative percent difference values are greater than zero then this means that the topographical level in the edge reel is higher than the topographical level in the middle reel. Accordingly the negative value of the relative percent difference can be interpreted as the middle position reel having a higher topography level as compared to that for edge reel.
A comparison between the edge and middle reels is performed separately for the uncoated and coated sides of reel in the following sub sections.

**Comparison among uncoated side of reels**

Fig 36(a) represent plots for the four uncoated paperboard reels. The top plot is the relative percent difference, between the edge reel R7 and its corresponding middle reel R8, and clearly shows that the edge reel has a higher topography than the middle reel throughout the full wavelength spectra. The differences are higher than 20% in the wavelengths at 0.3-0.8mm, 4mm and 10mm. This shows a reduced uniformity of the surface quality across the width of the paperboard.

Similarly the bottom plot in figure (a) also shows higher topography amplitudes in the edge reel R5 as compared to its corresponding middle reel R6 in most of the wavelength scale. However, there are exceptions at the beginning and at around wavelength 1.7 mm and 10mm wavelengths which provides the motivation to investigate this by means of a separate study.

Both the relative percent difference plots indicate that, on average, the edge reels have a higher topography as compared to their corresponding middle reels and this difference is higher for reels R7 and R8 compared to reel R5 & R6. In other words, reels R5 and R6 exhibit more uniformity across their web widths as compared to that for reels R7 and R8. The differences in different wavelength bands are represented in Table 7.

**Comparison among Coated side of reels**

In a similar manner to that of Fig 36(a), Fig 36(b) is also a relative percent difference comparison between the edge position and the middle position reels, but, for the coated sides. The plot of reels R5 and R6 is very close to the zero in the 0.1 to 1.25 mm range, which indicates that these reels have good uniformity of surface topography across the width of the webs in this wavelengths range. Whereas, in the same wavelength range, the second plot, the difference between reels R7 and R8, is fluctuating between -10 to +13% which shows a non uniformity of the topography between the edge and middle positions of the reels. Both plots have a sharp increase after 3 mm especially the plot of reels R7 and R8. The detailed topographical difference between the edge and the middle reels is analyzed and represented in the Table 7.

<table>
<thead>
<tr>
<th>Reel. No.</th>
<th>Comparison between</th>
<th>Surface</th>
<th>Relative percent difference Unit</th>
<th>Range of wavelength bands in mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.1-0.2</td>
</tr>
<tr>
<td>R5 &amp; R6</td>
<td>Edge and Middle Reel</td>
<td>Uncoated</td>
<td>%</td>
<td>-4.3</td>
</tr>
<tr>
<td>R7 &amp; R8</td>
<td>Edge and Middle Reel</td>
<td>Uncoated</td>
<td>%</td>
<td>5.0</td>
</tr>
<tr>
<td>R5 &amp; R6</td>
<td>Edge and Middle Reel</td>
<td>Coated</td>
<td>%</td>
<td>4.6</td>
</tr>
<tr>
<td>R7 &amp; R8</td>
<td>Edge and Middle Reel</td>
<td>Coated</td>
<td>%</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Fig 36 Comparisons of same family members of paperboards, edge reels vs. middle reels, in the form of Relative percent differences. Figure (a) is the plots for the uncoated sides and (b) for the coated sides of paperboard reels.

10.2 Conclusions

The online topography measurement and characterization provide opportunities to discover the surface irregularities in the wavelengths of interest. The measurements have been characterized, in the wavelengths spectra from 0.1 to 10 mm, which clearly show the details of the surface irregularities in each of the wavelength components. The results represented have achieved the fibre level roughness characterization in relation to the samples of different grades as well as to the samples of the same family grades, such as the edge and the middle position reels, where the topography differences are expected to be much smaller.

The developed prototype and the experimental results have proven that the exploitation of simple and economical laser triangulation techniques can be a valuable application for online surface topography measurements in the paper and the paperboard industries.
11 SUMMARY OF SCIENTIFIC PUBLICATIONS

11.1 ARTICLE I

The article emphasizes the surface physical property of paper focusing on the online measurement of the surface topography in the pulp and paper industry. The surface topography differences between the machine direction (MD) and the cross direction (CD) have been investigated in a wavelength spectrum for the various quality grades of 20 paper and paperboard samples in the laboratory. It was concluded that in the majority of the cases the CD measurement yields higher roughness data as compared to the MD in the shorter wavelengths. This publication proposes the measurement directions depending upon the type of the paper and region of interest in a wavelength bands.

11.2 ARTICLE II

It describes the importance and feature advantages of online surface roughness measurements over the laboratory measurement, in the paper and paperboard industry. Based on the conclusion of article I, an Online Topography (OnTop) device was designed which measures surface topography in the CD. The online roughness measurements were taken on 8 different grades of newspaper and paperboard reels on the moving paper web by the OnTop. All reels were classified on the basis of average roughness for both sides of each reel. The online results have successfully distinguished all the reels including the surfaces where the topographical differences are expected to be very low.

11.3 ARTICLE III

The online roughness measurements have many distinct advantages over the offline measurements but the surface measurement in the single value of average roughness does not provide the full detail with regards to the paper surface. In a continuation of publication II, the online raw data of the surface profile for the 8 newspapers and paperboard reels were further analyzed in a wide scale of wavelengths spectra from 0.1 to 10 mm. The detailed topographical properties for all sample reels were presented in each of the wavelength components, including roughness and waviness and it is also possible to extract cockling by this means. In general the successful characterizations were achieved for all reels, and in particular, the results have shown the differences for the topography levels for the samples which have the same family material and quality grades, such as edge and middle reels, which would otherwise be difficult to distinguish by the single value of roughness. Hence, the online topography analysis in a wide scale of wavelengths spectrum can measure and evaluate the surface in the fibre level of roughness which will be helpful in relation to keeping and maintaining the desired and uniform surface topography throughout the entire production in the paper and paperboard manufacturing industry.
11.4 Authors Contributions

The exact contributions of the authors of the three publications in this thesis are summarized in Table 8. In the table M and C represent the main author and co-author respectively.

Table 8 Authors’ Contributions

<table>
<thead>
<tr>
<th>Paper #</th>
<th>Main author</th>
<th>Co-authors</th>
<th>Contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>AA</td>
<td>JT</td>
<td>AA: Developed the algorithm and investigated the results. JT: Supervisor AM: Supervisor MO: Supervisor CW: Measurements performed on 20 samples. J.Lin: Measurements, discussions and review of manuscript. J.Lid: Technical discussion and review of manuscript.</td>
</tr>
<tr>
<td>II</td>
<td>AA</td>
<td>JT</td>
<td>AA: Developed prototype OnTop. Designed hardware, software, written algorithm for online measurements and taken measurements at pilot plant. Characterized all the 16 reels results. JT: Supervisor AM: Supervisor MO: Supervisor J.Lin: Selection and provision of Test materials and samples. Co-operation and co-ordination for the online measurements. Provided technical assistance and review the manuscript. J.Lid: Same as J. Lin above.</td>
</tr>
<tr>
<td>III</td>
<td>AA</td>
<td>JT</td>
<td>AA: Analyzed all the data and characterized the results for all the 16 sample reels in wavelength spectra. JT: Supervisor AM: Supervisor MO: Supervisor J.Lin: Technical inputs and review the manuscript. J.Lid: Same as J. Lin above.</td>
</tr>
</tbody>
</table>

Authors:
1. M. Anzar Alam (AA)
2. Jan Thim (JT)
3. Anatoliy Manuilskiy (AM)
4. Mattias O’Nils (MO)
5. Christina Westerlind (CW)
6. Johan Lindgren (J. Lin)
7. Joar Lidén (J.Lid)
12 THESIS SUMMARY AND CONCLUSION

The overall scope of the thesis is to present the experimental online characterization results for the various surface quality grades of paper and paperboard. The emphasis is given to measuring and analyzing the topography of the smooth and coated paperboard and to ensure that it is able to distinguish the surfaces belonging to the same quality grades. It provides information in relation to understanding and in providing a solution for the online topography measurements especially in the paper and paperboard mills.

The thesis has been organized so that it will be of assistance to readers of science and technology including researchers and students. However, the research work presented is of direct interest to those who are involved in the study of surface science, fundamental experimental and applied research, advanced measurement science, monitoring and recording paper surface physical phenomena in real time, and the surface and coating technologist.

12.1 IMPORTANCE OF SURFACE TOPOGRAPHY AND MEASUREMENTS

The thesis introduction describes the importance of the surface topography, in general, and the surface topography for the paper and the paperboard in particular. Background information has been provided regarding the importance of accurate topography measurements and discusses the available offline topography measurement techniques and emphasises the need for online measurements together with the main contribution of the thesis.

12.2 LAB AND ONLINE MEASUREMENT TECHNIQUES

The traditional and conventional techniques used to measure surface topography have been described and their limitations are discussed. The requirement for online measurements has been addressed. A number of new measurement techniques and methods have been mentioned in brief and their applications presented.

12.3 IMPORTANCE OF MEASUREMENT DIRECTIONS IN CD AND MD

The paper surface has been studied in relation to the anisotropic properties and fibre orientation in the cross direction and the machine direction as these can play an important role in selecting the preferred measurement direction for the online device in the paper mills. The investigation of the topographical differences between the CD and the MD has also been conducted by using 20 different grades of paper and paperboard samples and it was revealed that the measurement in the CD yields large topographical data in the shorter wavelengths.

12.4 BRIEF DESCRIPTION OF ONLINE DEVICE THE OnTop

In relation to the recently developed device, the Online Topography (OnTop), the design principle and measurements techniques have been described. The authentication of the OnTop was achieved by offline and by online measurements.
The steps have been discussed and their correlation results presented. The linear regression match between offline and online measurements were found 82% to 96% for newspaper and paperboard reels respectively.

12.5 **ONLINE MEASUREMENT AND CLASSIFICATION OF SAMPLE**

The main part of the thesis results are based on experimental work in the laboratory and in the Pilot Coater at Iggesund paperboard in Sweden. The online surface measurements and the classification of 8 different grades of samples reels, including the wireside and topside of the newspaper reels, and uncoated and coated sides of the paperboards reels, on the basis of average roughness have been presented in detail.

12.6 **ONLINE MEASUREMENT AND CHARACTERIZATION IN WAVELENGTH SPECTRA**

In this section the essence of the thesis was described which involved the online surface topography measurement and analysis in a wide scale of a wavelength spectrum. It was described that the online roughness measurement has many advantages over the traditional laboratory measurement, but, it provides roughness of the whole measurement in a single variable and this is not sufficient to characterize the surface in detail. Therefore, the online data of the 8 sample reels were further analyzed in a wavelength spectrum in order to characterize each sample reel comprehensively in the 0.1 to 10 mm spatial wavelength range. The successful characterization of all sample reels, in general, has been achieved, and in particular, the comparison results, among the reels of same family materials and quality grades, such as the edge position and the middle position reels, have been able to distinguish distinctly between each reel in the wavelength spectrum.
13 REFERENCE


