Contributed paper

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A diffractive optical element based machine vision system for local optical inspection of compressed paper

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Surface quality of fine and supercalendered (SC) paper samples was investigated by using a pressure gauge together with a machine vision system. It is shown in this study that a machine vision system that exploits diffractive optical element (DOE) along with a focused laser beam detects local specular reflectance variation of the compressed paper. It is suggested that this machine vision system can be utilized for inspection of optical quality variations of compressed paper.

Keywords: diffractive optical element, local specular reflectance, paper compressing.

1. Introduction

Optical properties of paper, such as opacity and colour, are important for quality of printing papers. Quality of the paper is typically varying across the web at the paper machine. Due to fluctuations in thickness, density, and porosity, the paper quality is a subject to local variations. The demand of attaining good paper quality becomes even more severe when using recycled paper in the pulp. It is obvious that there is an ever increasing demand on optical metrology that can be utilized at a production line and in a laboratory, and that assists the paper makers to optimise the quality of their products.

In this paper, we describe an apparatus that is based on the use of a pressure gauge in context of a diffractive optical element based sensor. The idea of using a pressure gauge stems from the fact that under an external pressure there appear dark and light patterns on the paper which is in contact with an optical probe window. In a previous study [1], which was based on the measurements using a spectrophotometer with an integrating sphere, it was observed that the wavelength-dependent reflectance from a macroscopic area of the paper is decreasing as a function of the applied external pressure. The conclusion of that study was that the patterns that are seen dark are in contact with the probe window, whereas domains of presenting light patterns are not in contact with the probe window. In this paper we go beyond the previous study in the sense that we investigate also local changes of the optical properties of the dark and light patterns. This is accomplished by utilization of a DOE as an analyser of light that is reflected to the specular direction from a small spot on the paper. Therefore, this sensor provides information about the local specular reflectance of the compressed paper. We have already experience of the DOE application for assessment of the surface texture of paper [2], print quality [3,4] and also quality of paper coating [5].

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2. Experimental

Two different paper samples: fine and supercalendered (SC) papers were investigated in this study. The investigated sample of the fine paper was double-coated and supercalendered and it was made from 100% chemical pulp. The analysed SC paper was a basic rotogravure grade and it contained 70% mechanical pulp. The differences in manufacturing process and in raw materials between analysed samples cause differences in optical properties of the samples as it can be seen in Table 1. The results of Table 1 were measured according to Tappi standards. In all measurements, only the topside of the sheet was analysed.

Table 1. Properties of the investigated samples.

Paper sample	Basis weight (g/m^2)	Thickness (mm)	PPS-smoothness[a] (mm)	Gloss (%)	Brightness (%)
Fine	98.1	73.0	0.92	74.1	88.7
SC	55.6	48.6	1.33	49.2	64.4

[a]Parker Print Surf – smoothness

The paper samples were investigated using a pressure gauge. The lateral probe window construction of the pressure gauge is shown in Fig. 1. Compression between the

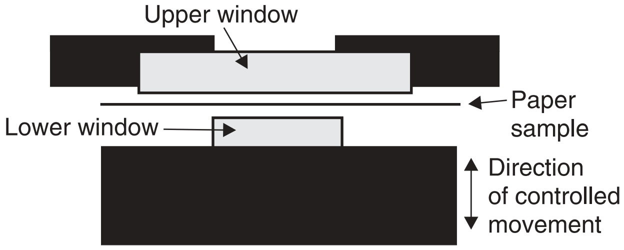

Fig. 1. Schematic diagram of the probe window construction of the pressure gauge.

upper and the lower window can be changed using pressurized air. The pressure can be tuned continuously from 0.3 MPa up to 6.0 MPa. Material of both windows was sapphire (Al_2O_3) and it was optical quality.

The machine vision system that was developed during the present study is shown in Fig. 2. The pressure induced light and dark patterns can be recorded by a CCD-camera and illuminating the probe window by non-polarized white light, which traverses through the upper window and scatters from the paper sample. Although the whiteness of the paper depends on surface roughness and illumination conditions [6], the illumination condition of the present system is not so important for the phenomenon described below. Before the laser light propagated through the lenses its intensity was decreased using a semi-transparent mirror, when the upper CCD-camera in Fig. 2 was used as a recorder. Therefore, the detected light would not be too bright for the cell of the CCD-camera. The system was aligned in a manner that the back reflections from the surfaces of the optical components, such as the probe window and beam splitters (BS), were spatially resolved from the signal. The laser radiation that is scattered from the paper and incident on the DOE (a computer-generated hologram) generates a 4×4 light spot matrix on the focal plane of the DOE and the size of one spot in the matrix is approximately 10 μm. The DOE was written by using an electron-beam writer. The theory and the imaging properties of the DOE can be found in Ref. 7. The appearance of the DOE is shown in Fig. 2(a) and the reconstructed image pattern in Fig. 2(b). The signal that was produced by the DOE was detected by another CCD-camera, while the intensity of the laser beam was not decreased using the semi-transparent mirror.

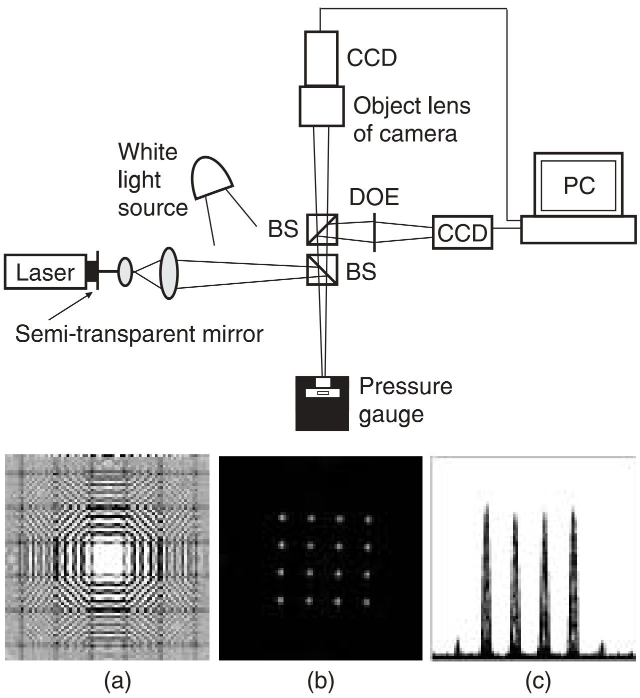

Fig. 2. Schematic diagram of the machine vision system with a HeNe-laser and the DOE; (a) an image of the DOE, (b) an image of the pattern of the light spots from the DOE, and (c) a lateral intensity distribution of the light spots projected on a plane.

3. Results and discussion

When using exclusively the white light source, light and dark patterns were distinguished. Such patterns could be observed even by ocular analysis from the SC paper. When the pressure applied to the paper is increased, the size of dark areas clearly expanded. When the pressure is decreased, the dark areas diminished and the light areas expanded. Typical images for the fine paper at two different pressures are shown in Fig. 3.

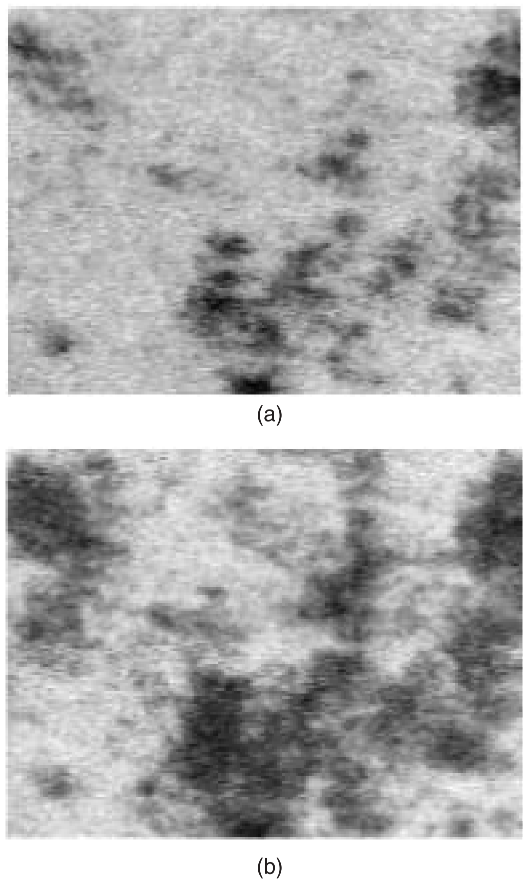

Fig. 3. Development of dark areas on surface of the fine paper. (a) pressure = 1.2 MPa, and (b) pressure = 2.4 MPa. The image size is 2.85×3.8 mm.

First, in order to obtain information about the local optical properties of the paper on the area of a dark or a light pattern, measurements using only the focused laser beam were performed. That is to say machine vision system without DOE and the lower CCD- camera in Fig. 2. Indeed, we studied details of the paper surface structure by observing the locations of the light and dark patterns and simultaneously using the focused laser beam that was scanned over a chosen region of the sample. The diameter of the laser spot on the surface of the paper sample was 100 µm. It was always observed that the image of the focused laser beam was bright on the light areas and dimmed or absent on the dark areas independent on the paper grade. A typical example related to the SC paper is shown in Fig. 4(a). In Fig. 4(b), the intensity curve I_{mean} is the mean value of the intensities of all image pixels as a function of scanned distance, except the 100 pixels that include the image of the laser spot. The intensity curve $I_{spotmax}$ is the corresponding maximum intensity of the laser spot on the paper surface.

The simple machine vision system using a focused laser beam is a corroborative method that confirms, according to the results in Fig. 4, the results of the spectrophotometric reflectance study [1]. In other words, the refractive index of the paper sample and the refractive index of the window have a better match on the dark areas of the samples than on the light areas. When the laser beam was focused on these dark (contact) areas, most of the laser beam propagated through the interface of probe window and the paper sample, and only a small part of the laser beam was reflected from the paper sample. Therefore, the laser spot is absent, e.g., in the middle part of Fig. 4(a) at the distance of 0.6 mm. On the contrary, most of the laser beam was reflected (scattered) from the paper sample, when the laser beam was focused on the light areas. In that case, the laser spot constitutes a bright spot image. Thus, using the fo-

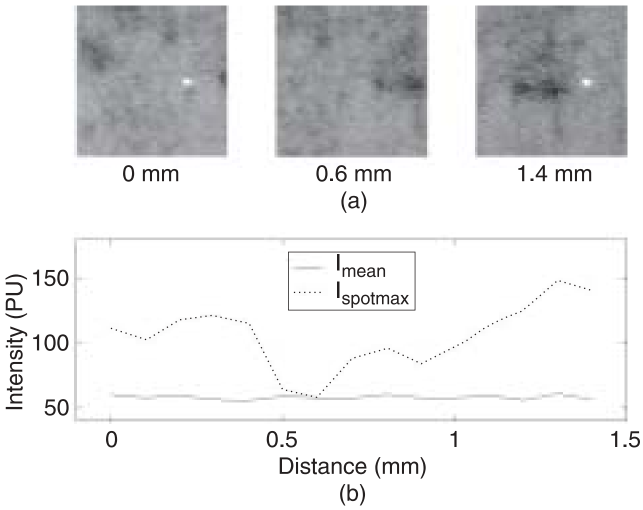

Fig. 4. (a) Laser beam focused on the SC paper at scanned distance 0 mm, 0.6 mm and 1.4 mm. (b) The mean intensity of the image pixels without pixels of the laser spot I_{mean} and the maximum intensity of the laser spot $I_{spotmax}$ as a function of scanned distance. The unit of intensity is pixel unit PU. The applied pressure was 3.3 MPa.

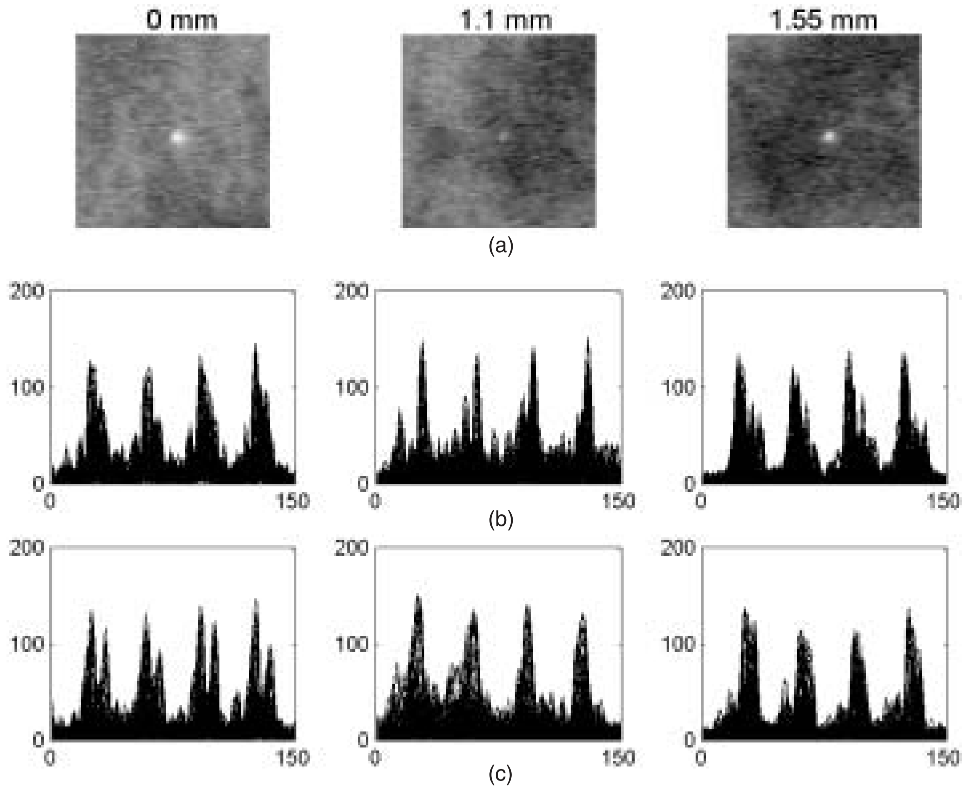

Fig. 5. (a) Laser beams focused on the fine paper at scanned distances 0 mm, 1.1 mm, and 1.55 mm, (b) in y-direction projected DOE signals from the same locations and (c) in x-direction projected DOE signals from the same locations. The applied pressure was 4.2 MPa.

cused laser beam, it is possible to detect, whether a spot of 100 μm in diameter on the paper sample is in contact or not with the upper window. If better spatial resolution is needed, it is possible to attain a spot diameter of the order of 1 μm for the focal point of the laser beam, such as in the case of laser profilometry [8].

Next, the DOE was implemented into the machine vision system. Then more specific information can be obtained concerning optical properties of the samples. Exemplary images are presented in Fig. 5. The focused laser beam was on a light area in the left and right sub-figures, and the beam was on a dark area in the middle sub-figure. The interesting finding was that information of the DOE signals was quite different from the image data obtained using the focused laser beam only. In the case of Figs. 5(b) and 5(c), the spikes of the DOE signal are relatively high also from the dark area for the fine paper. This is believed to result from a relatively strong specular reflection from that particular location. With the analysed SC and fine paper samples it was observed that there is no regularity in the height of the spikes versus the visual appearance of the light or dark pattern. In some location of the dark pattern one may record either a low or a high signal and same holds for the light patterns. Nevertheless, this is what actually can be expected in the case of paper, namely the local reflection coefficient of paper is certainly varying due to the non-homogeneity of the paper surface. The non-homogeneity of paper, e.g., laser print paper, can be seen with a naked eye just by observing the light transmission against a white light source. Obviously, the DOE sensor can be used for assessment of a change of small-scale optical properties of the paper such as reflectance. The local gloss variations of compressed paper, which has some basic research importance, can be measured by comparing the intensity distributions such as those in Figs. 5(b) and 5(c) with the ones obtained from a mirror surface. Actually, we have already demonstrated the high sensitivity of the DOE sensor to provide information on local gloss variation [9–11].

4. Conclusions

It was previously observed that white light-induced dark patterns are due to the contact between the probe window and the compressed paper, which experiences the external pressure. The amount and nature of the contact is believed to depend on structural properties of paper such as surface roughness, formation, and compressibility. The present study using exclusively the focused laser beam supports the previous conclusion about the contact or lack of contact between the paper and the probe window. Such information may be utilized in the quality assessment of uniformity of the paper surface contact with the probe window in laboratory conditions. The diameter of the laser spot, which was 100 μm in these measurements, defines the spatial resolution of the measurement.

Both in dark and light areas one can find local differences in small-scale optical properties of the paper by using the machine vision system employing the DOE. The DOE can be used to detect local variation of specular reflectance of the compressed paper. Thus, the focused laser beam and the DOE complement the first generation version of the machine vision system that detects macroscopic dark and light patterns on compressed paper, but using the white light source only. The present machine vision system can be generalized also for the optical inspection of other materials such as cardboard and textiles. In principle, the suggested machine vision system provides means also to estimate the local refractive index of the compressed medium at a given wavelength of coherent laser radiation but it requires further experiments and theoretical treatment of the problem, which is beyond the scope of the present study.

Finally, we wish to emphasize that the DOE produces an image that is due to the combination of the intensity and the phase of the scattered wavefront, whereas in the case of focused laser beam the CCD-camera detects only the intensity of the scattered wave front.

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