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Abstract. We present a method of measure of the roughness of the paper based on the analysis of a speckle pattern on the surface. Images of speckle over the surface of paper are captured by means of a simple configuration using a laser, beam expander, and a camera charge-coupled device (CCD). Then we use the normalized covariance function of the fields, leaving the surface to find the roughness. We compare the results obtained with the results obtained with a confocal microscope and the Bendtsen method that is a standard of the paper industry. This method can be considered as a noncontact surface profiling method that can be used online. [DOI: 10.1117/1.3625418]

Subject terms: roughness; paper; speckle.

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1 Introduction

One of the central problems in the industry of paper is the roughness of the surface of the paper that is a very important parameter in the manufacture of paper.[1,2] The roughness parameter most commonly used is the arithmetic mean [Eq. (1)] of the absolute values of the heights measured from the centerline (Fig. 1).

Mathematically, it is very simply defined in terms of the surface height variations δh_i measured from the mean surface level:

$$R_a = \frac{1}{N}\sum_{i=1}^{N} |\delta h_i|. \tag{1}$$

An alternative measure of the average variation in surface height is the root-mean-square roughness. This is the quantity commonly used in the optics industry. It is defined as

$$\sigma_R = \left[\frac{1}{N}\sum_{i=1}^{N} \delta h_i^2\right]^{1/2}. \tag{2}$$

There will obviously be some definite relationship between R_a and σ_R. However, this will depend on the particular statistical distribution of surface height present in any given case. In the industry, the relationship usually assumed is[3]

$$\sigma_R = 1.11 R_a. \tag{3}$$

The multiplying factor will, however, be larger for surfaces with abnormally high numbers of large deviations from the mean surface height.

2 Measurement of the Surface Roughness

Researches have been investigated and developed techniques of contact and noncontact suitable for measuring the roughness of the paper. Among the most common measurement techniques are: airflow, profilometry (mechanical and optical), interferometry,[4] atomic force microscopy,[5] confocal scanning microscopy techniques,[6] optical correlation,[7–9] triangulation, and speckle metrology. In general, many of these techniques can be used only in laboratory conditions, i.e., outside the industrial manufacturing process.

2.1 *Air Leak Methods*

Air leak methods currently are the standard test for measuring surface roughness. The air leak rate between the paper surface being measured and a specific flat surface is recorded using specialized pneumatic devices. Methods differ in the pressure on which the measuring surface is pressed to paper, measured quantity (time, volume), softness of the flat surface, or measured area. Bendtsen roughness is achieved by clamping the test piece between a flat glass plate and a circular metal surface and measuring the rate of airflow between the paper and the metal surface.[10,11] Bekk smoothness is again measured by the air leak method but, unlike the previous instrument, air is drawn across the surface of the test piece under partial vacuum.[12]

2.2 *Profilometers*

Profilometers measure the actual topography of a surface. This method of measuring surface roughness is to pass a mechanical or optical stylus probe across the surface and measure its movement as it follows the surface profile. This technique has been developed to a very sophisticated level and can achieve surprisingly high precision.[13] However, there are limits set by the finite radius of the tip of the probe; for example, peaks that are narrower than the probe tip will still be followed by the probe but will be recorded as being broader than they really are, while the probe will be physically incapable of reaching the bottom of the narrow fissures. In

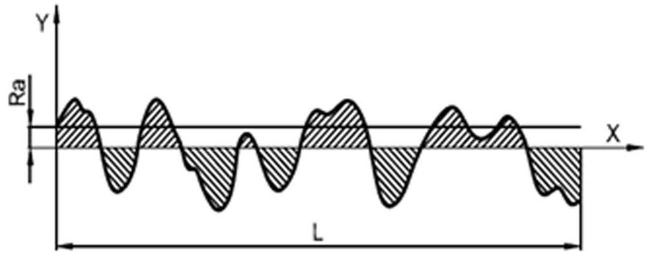

Fig. 1 Definition of R_a.

other words, some of the surface height information is being filtered out. Results also seem to depend on the actual shape of the stylus and on its loading. In addition, many applications as in paper are unsuitable for contact techniques, which could damage the surface. Finally, profilometers are too slow for online use.

2.3 *Speckle*

Surface roughness measurement can also be accomplished by a speckle-based instrument. A surface speckle pattern, which is a grainy structure produced by scattered light from a rough surface when illuminated by coherent light, contains rich information about the surface roughness.

With the advent of lasers in the 1960s, researchers have discussed the relationship between surface roughness and the statistical properties of speckle pattern. We have seen that speckle metrology has the potential to obtain measurements of the surface roughness.[3,14,15]

Table 1 Results of the measurement of the roughness obtained with confocal microscope, Bendtsen method, sum of the values of μ_a ($r > 20$) and the equivalent roughness for 14 papers.

No.	Ra(Confocal) (micres)	Bendtsen (ml/s)	$(\sum\mu_a(r>20)10^{-2}$ [a]	$\sigma = [\ln(1/\sum\mu_a)]^{1/2}$
1	6,5	1150	0,0284	2,45
2	6,2	1100	0,0261	2,44
3	6,1	700	0,0284	2,42
4	6	750	0,0304	2,41
5	6	750	0,0256	2,44
6	5,7	850	0,0282	2,42
7	5,5	800	0,0333	2,39
8	4,2	75	0,0366	2,37
9	4,3	80	0,0373	2,36
10	3,7	190	0,0458	2,32
11	3,4	120	0,0508	2,30
12	3,4	60	0,0523	2,29
13	3,4	55	0,0531	2,29
14	3,3	125	0,0501	2,30

[a] We multiply by 10^{-2} to avoid negative numbers in the logarithm.

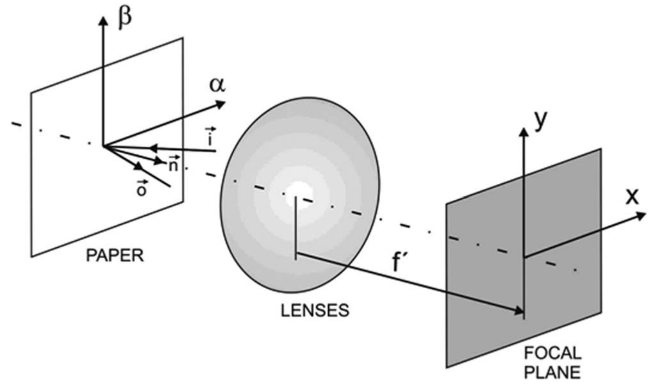

Fig. 2 The intensity in the plane(x,y) is the Fourier transform of the normalized covariance function of the waves leaving the surface in the plane (α,β).

Researches have been developed and used different methods to study the surface roughness by speckle techniques. These are based on the study of speckle contrast[16] and others use the speckle correlation,[17–20] which have been shown to give good results, for studying metal surfaces, dielectric fluids, and paper.

3 Theory and System Set-up Configuration. Computation of the Normalized Autocorrelation Function μ_a

When we project a monochromatic plane wave over a surface that is assumed to be rough and its correlation function depends only on the differences of measurement coordinates, then the relationship between the height variations of the surface and the amplitude variations of the scattered wave is, in general, an extremely complex one, influenced by variations of surface slope on reflection, multiple scattering, and shadowing. We adopt an oversimplified model that implies that the scattered complex amplitude just above the surface is related to the surface height by a geometrical approximation that assigns a phase φ to the scattered complex amplitude that is the phase delay associated with propagating to the surface and scattering from the surface.
Then

$$\varphi(\alpha, \beta) = \frac{2\pi}{\lambda}(-\vec{i}.\vec{n} + \vec{o}.\vec{n})h(\alpha, \beta) \tag{4}$$

where φ is the phase, $h(\alpha, \beta)$ is the surface height, λ is the wavelength and $\vec{i}$, $\vec{o}$, and $\vec{n}$ are the unitary vectors of incidence, reflection, and normal to the surface, see Fig. 2.

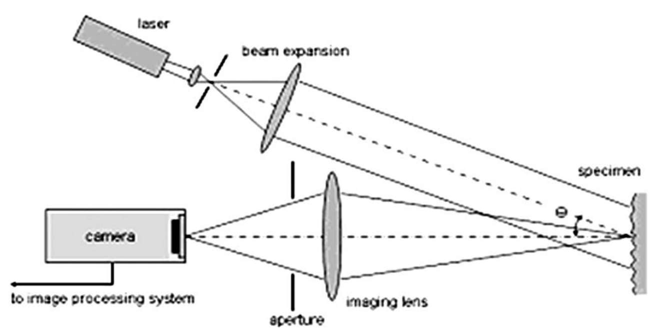

Fig. 3 Experimental system.

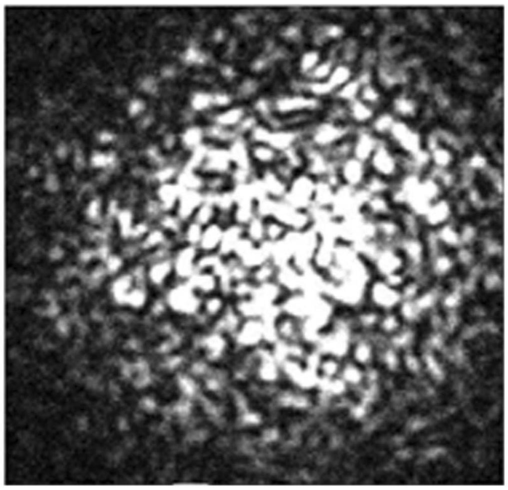

Fig. 4 One of the images of speckle taken.

With this approximation the variance of the phase shifts σ_φ is related to the variance of the surface height fluctuations σ_h through[17]

$$\sigma_\varphi^2 = \left[\frac{2\pi}{\lambda}(-\vec{i}.\vec{n} + \vec{o}.\vec{n})\right]^2 \sigma_h^2. \tag{5}$$

The normalized autocorrelation function of the field leaving the surface is defined as:

$$\mu_a(\Delta\alpha, \Delta\beta) = \frac{\Gamma_a(\alpha_1, \beta_1, \alpha_2, \beta_2)}{|r|^2 I_{inc}}, \tag{6}$$

where Γ_a is the autocorrelation function of the field, r is the average amplitude reflectivity of the surface, and I_{inc} is the intensity incident on the scattering area.

Making the assumptions that $\varphi(\alpha, \beta)$ is a Gaussian random variable and that the surface height correlation function is also Gaussian, then it can be shown[17] that:

$$\mu_a(r) = \exp\left[-\sigma_\varphi^2(1 - e^{-(r/r_c)^2})\right], \tag{7}$$

where $r = \sqrt{\Delta\alpha^2 + \Delta\beta^2}$ and r_c is a constant. The greater $\sigma_{\varphi,}$ more rapidly μ_a will tend to zero as r grows. So, we can relate the sum of the values of μ_a far from the center ($r >$ 20) to σ_φ through Eq. (7) and we may define σ as:

$$\sigma = \sqrt{\ln\left(\frac{1}{\sum_{r>20}\mu_a(r)}\right)}. \tag{8}$$

3.1 *Calculation of* μ_a

The Van Cittert–Zernike theorem is a result of the coherence theory that states that under certain conditions the Fourier transform of the mutual coherence function of a distant, incoherent source is equal to its intensity.

When applied to the fields leaving the scattering surface of paper, the Van Cittert–Zernike theorem[17] provides us with a connection between the normalized autocorrelation function of the fields leaving the scattering surface of paper and the average intensity distribution observed in the focal plane of a positive lens

$$\overline{I(x, y)} \propto \int_{-\infty}^{\infty}\int \mu_a(\Delta\alpha, \Delta\beta) e^{-j(2\pi(x\Delta\alpha + y\Delta\beta)/\lambda f)} d\Delta\alpha\, d\Delta\beta \tag{9}$$

where μ_a is the normalized autocorrelation function, f is the focal length of the positive lens used, and λ is the wavelength of the laser used. Thus, if $\overline{I(x, y)}$ is carefully measured, using a detector that is large enough to average over many

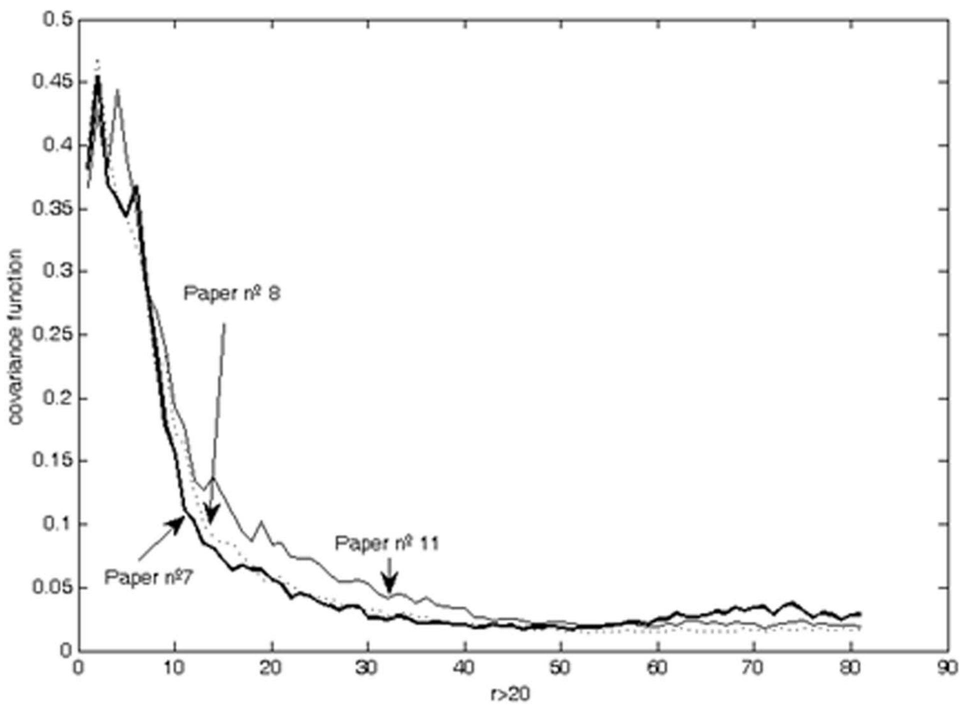

Fig. 5 Values of the covariance function for three different papers. Paper numbers 7, 8, and 10 are in Table 1.

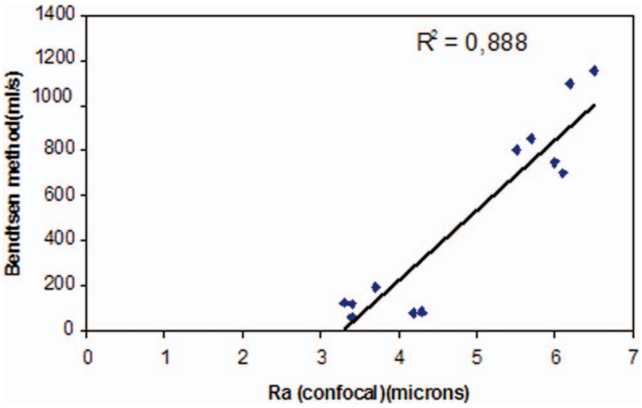

Fig. 6 Comparison between the measurements using confocal microscope and the Bendtsen method.

individual speckles, a normalized inverse Fourier transform of the intensity distribution would provide μ_a at the scattering surface.

4 System Set-up and Configuration

The system used for measurement consisted of the following elements (Fig. 3): A He–Ne laser of 5 mW with a wavelength of 632.8 nm, a charge-coupled device (CCD) camera UNIQ UM-301, 752 × 582 pixels and a beam expander. The camera is located in the direction normal to the sample. To form the speckle pattern, subjective speckle is used.[6,13,15] The field of view is 10 × 10 mm. The format of the images was 200×200 pixels, and 256 gray levels.

The laser beam is expanded and projected on paper, with an angle $\Theta = 15$ deg from normal, obtaining a speckle pattern of about 1 cm in diameter. Figure 4 shows one of the images obtained. Computer programs used for capturing and analyzing images of the speckle pattern are: Matrox Imaging (Intellicam module) and MATLAB (Digital Image Processing Toolbox).

5 Results

We characterized the roughness of 14 different types of paper with R_a between 3.3 and 6.5 μm with similar optical proprieties using an optical method [a confocal microscope optical three-dimensional profilometer operating in confocal mode, an air leak method (Bendtsen), and the sum of the values of μ_a ($r > 20$)]. In Fig. 5 we show the values of μ_a ($r > 20$) for three different papers. In Fig. 6 we show the relationship between R_a (Confocal) and Bendtsen, and in Fig. 7 we show the comparison between the measurements using confocal microscope and our method

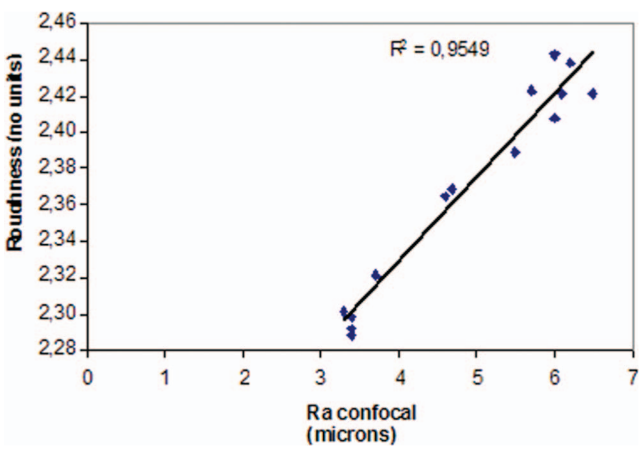

Fig. 7 Comparison between the measurements using confocal microscope and our method.

6 Conclusions

In this work, we have developed a method to find the roughness of paper using speckle. Using the proprieties of the normalized covariance function that we obtain from the image of the speckle through the inverse Fourier transform, we relate the values of the normalized covariance function far from the center with the roughness of the paper. In order to test the method we have characterized the roughness of 14 papers in the range between 3.3 and 6.5 μm using a confocal microscope. The results present a good correlation between them ($R^2 = 0.9545$). The results are better than the comparison between a standard method (Bendtsen) and the confocal microscope. The method is easy to implement and can be used during the manufacturing process.

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