Surface roughness measurement through a speckle method

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Abstract. An optical approach for real-time measurement of statistical parameters associated with rough surfaces is proposed. Two crossed-polarized, partially correlated, speckle patterns originated from a surface under different illumination conditions are recorded on a linear photodiode array. The r.m.s. surface roughness is related to the correlation degree between both speckle patterns, which in turn is derived by processing the detected intensity distribution. Some experimental results are shown in order to illustrate this technique.

1. Introduction

Several optical methods have been proposed in order to measure the statistical parameters associated with diffuser surfaces using the properties of scattered light. Depending on the r.m.s. roughness value of the inspected surface, two different approaches seem to be appropriate. For surfaces having a r.m.s. roughness from 0·01 to about 2 μm, the methods based on Beckmann's model for the light scattering distribution provide a non-contacting roughness measurement through a transference curve optical-to-mechanical parameter, which depends on the machined type of the surface [1–4]. For a more restricted range (r.m.s. from 0·05 to 0·25 μm), Asakura *et al.* [5–8] proposed a method in which the roughness value is obtained by measuring the average contrast of the image speckle pattern originated from the surface under coherent illumination, and varying the imaging conditions of the optical system.

On the other hand, for larger surface roughness, in the range 1–30 μm, a different approach, in which the surface information can be derived from the correlation properties of the speckle patterns produced by the surface under different illumination conditions, gives better results. Léger *et al.* [9] analyzed the correlation degree of two speckle patterns originated by the test surface, each one obtained from a light beam having slightly different angles of incidence. Both speckle patterns are successively recorded by double exposure on the same photographic plate. In a second step, by performing an optical Fourier transform of the developed plate, Young's interference fringes are produced. They derived a theoretical relationship between the visibility of these fringes, and the values of the surface roughness and the several geometrical parameters involved. Based

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on this principle, they proposed a method where the surface is simultaneously illuminated by two coherent light beams with different and variable angles of incidence through an afocal lens system [10]. A Michelson interferometer is used in order to collect and combine the speckle patterns formed by the scattered light beams in two different directions. It is shown that the resulting speckle pattern diffraction at infinity is partially correlated, and from the visibility of the interference fringes that are obtained the roughness value of the surface can be derived.

In order to get a real-time measurement for practical cases, the above mentioned procedure becomes rather difficult to implement. For this reason, in this paper we propose a speckle correlation method employing an optical arrangement which is suitable for performing fast and continuous measurements of surface roughness. These changes are considered taking into account industrial environmental conditions, so that the influence of factors such as misalignments or vibrations on the system performance is minimized. The signal processing algorithm used by the optoelectronic system can yield a measuring rate of about ten roughness values per second.

In section 2, a description of the method is presented, and a discussion of the influence of the several parameters involved on the measuring accuracy follows. Next, in section 3, some experimental results obtained by using plane-ground comparison standards are shown to illustrate this approach. Finally, in section 4, we summarize the advantages and limitations of this method.

2. Principle of the method

As shown in figure 1, the coherent light beam emerging from the laser source is split into two crossed-linear polarized light beams by the polarizing cube beamsplitter PBS. Both light beams are combined by the beamsplitter BS, in such a way that the surface S under study is simultaneously illuminated by two light beams, Σ_1 and Σ_2, with angles of incidence θ_1 and $\theta_1 + \Delta\theta_1$. The angular separation $\Delta\theta_1$ between Σ_1 and Σ_2 can be selectively changed by rotating the mirror M_2. The motion of the mirror is synchronized with the output of a camera LG_1, provided with a linear photodiode array, which measures $\Delta\theta_1$ through the
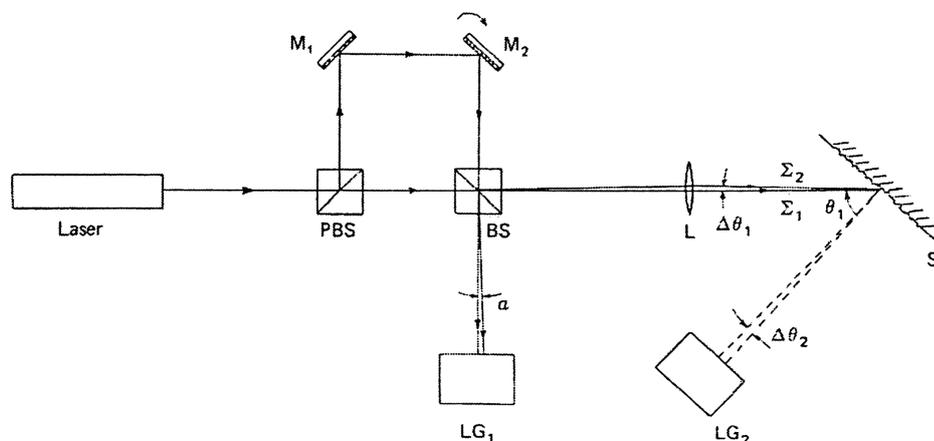

Figure 1. Optical system configuration.

relationship $\alpha = m \, \Delta\theta_1$. m being the magnification of the lens L. As the illuminating beams Σ_1 and Σ_2 have crossed-linear polarization states, two (non-interfering) speckle patterns are scattered by the surface S. If we choose the normal to the surface as the viewing direction (i.e. $\theta_2 = 0$), then the whole intensity distribution detected by a second linear camera LG_2 can be considered as the speckle pattern originated only by Σ_1, and a shifted version of that speckle pattern by an amount $\Delta\theta_2$, originated by Σ_2, and where

$$\Delta\theta_2 = \cos\theta_1 \, \Delta\theta_1 \, . \tag{1}$$

In addition, the intensity distribution of each individual speckle pattern also changes, so that their correlation degree decreases as $\Delta\theta_1$ increases. As was established in [9], if a recording of such intensity distribution were Fourier transformed, Young's fringes would appear with a visibility V given by

$$V = \exp\left[-(2\pi R_s \sin\theta_1 \, \Delta\theta_1/\lambda)^2\right], \tag{2}$$

R_s being the standard height deviation of the surface. It is to be noted that equation (2) was derived under the assumption of a normally distributed surface.

In the case examined, an interference fringe pattern is not produced, so equation (2) cannot be directly applied to obtain the roughness value of the surface. However, since we want to relate the correlation degree between the scattered speckle patterns with a roughness parameter, the Fourier transformation which would originate the interference fringes is replaced by a simplified one-dimensional autocorrelation product of the intensity detected by the linear photodiode array. This operation also takes into account the statistical behaviour of the partially correlated speckle patterns. Thus, a transference curve can be obtained from which the roughness value is measured, with θ_1 and $\Delta\theta_1$ as known geometrical parameters.

If the camera LG_2 is located at a distance D from the surface S, far enough away for the Fraunhofer approximation to be valid, then the linear separation Δx between both speckle patterns at the plane of the photodiode array becomes

$$\Delta x = D \cos\theta_1 \, \Delta\theta_1 \, . \tag{3}$$

Therefore, the detected intensity distribution consists of a collection of speckle pairs, with a speckle separation for each pair given by equation (3), and with an average value size δx for each individual speckle grain:

$$\delta x \simeq 1 \cdot 22 \, \lambda D/a \, , \tag{4}$$

where a is the diameter of the illuminated area of S. If N is the number of photodiodes in the array, and Δx_0 is the spacing between adjacent photodiodes, the two following conditions should be fulfilled in order to get enough spatial resolution for processing the speckle intensity

$$\Delta x > \delta x \gg \Delta x_0, \qquad N\Delta x_0 \gg \Delta x \, . \tag{5}$$

In this case, the information content of each speckle grain can be recovered, and furthermore, several speckle pairs can be adequately processed.

As was previously stated, for measuring the correlation degree between both crossed-linear polarized speckle patterns, a one-dimensional autocorrelation operation $W(x)$ of the resulting intensity distribution is performed. From $W(x)$, we are only interested in the value that this function takes when $x = \Delta x$: (the

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speckle pattern separation). Taking into account the sampling nature of the recording procedure, the algorithm employed in order to carry out the intensity processing is a discrete autocorrelation operation which can be expressed as

$$W_k = \sum_{i=1}^{N} I_i I_{i+k} \,.\tag{6}$$

In equation (6), the following assumption is made: $I_j = 0$, if $j > N$; and the value of $k = \Delta x / \Delta x_0$ is selected so as to be an integer.

Now, we want to relate the intensity autocorrelation W_k with a surface roughness parameter in a similar way as was theoretically established by equation (2) for the case of the fringe visibility V. If we consider only one speckle pair from the detected intensity, the normalized autocorrelation $W = W_k / W_{k=0}$ can be thought as proportional to the quotient between the transmittance values associated with each speckle grain. In turn, this quantity is responsible for the contrast of the fringe pattern which the speckle pair would originate under Fourier transformation. Thus, it can be concluded that, as in the case of the interference fringes, a relationship: $W = W(R_s; \theta_1; \Delta\theta_1)$ can be stated, and where the specific function dependence is given, in each particular case, by the statistical behaviour of the surface. For a Gaussian distribution, such a relationship takes the form of an exponential function. Therefore, with a fixed value of θ_1, the surface roughness parameter is obtained through the transference curve $W = W(R_s; \theta_1; \Delta\theta_1)$, the value of $\Delta\theta_1$ being selected (by rotating the mirror M_2) in such a way that the measured autocorrelation value of W falls in the maximum change domain of the curve.

In the next section, we show some experimental results in order to illustrate the discussed method. Now, we analyse the influence of external features on the optical arrangement, such as surface vibration and tilt, on the system performance. We start by considering a vibration motion in the direction joining the surface S with the camera LG_2, with an amplitude A_z and a frequency ν. If ν_0 is the scanning frequency of the photodiode array, two cases can be considered: $\nu_0 \gg \nu$, and $\nu_0 \leq \nu$. In the first one, since the detection process takes place in a time interval very short compared with that associated with the surface oscillation, the roughness measurement is not affected by the vibration motion. In the second case, since the measuring time is comparable with the oscillation time, the value of A_z should be less than the average longitudinal size of the speckle grains δ_z in order that the roughness measurement should not be greatly affected by the surface vibration. Thus: $A_z < \delta_z \simeq \lambda D^2 / a^2$. In most practical cases, this condition is satisfied since $1 \text{ mm} < \delta_z < 5 \text{ mm}$.

For the case of surface tilting, equation (1) should be replaced by

$$\Delta\theta_2' = \cos\theta_1 \, \Delta\theta_1 \, (1 - \tan\theta_1 \, \delta\theta_1) \,,\tag{7}$$

where now $\theta_1 + \delta\theta_1$ is the angle of incidence for the Σ_1 light beam. Therefore, the speckle patterns separation changes in the following way

$$\frac{\Delta x'}{\Delta x} = 1 - \tan\theta_1 \, \delta\theta_1 \,.\tag{8}$$

For a tilt angle $\delta\theta_1 = 2°$, and $\theta_1 = 45°$, the separation between the speckle patterns changes 3.5 %.

3. Experimental results

The optical arrangement shown in figure 1 was implemented in order to test this method. The light source was a 2 mw He–Ne laser, $\lambda = 0{\cdot}633$ µm. Two linear cameras LG_1 and LG_2 were used, each one provided with a 512×1 photodiode array. The spacing between adjacent photodiodes was: $\Delta x_0 = 13$ µm. and the scanning time was 200 µ s. The distance D between the camera LG_2 and the surface S was selected as $D = 170$ mm, and the diameter of the illuminated area of S was $a = 2$ mm. Therefore, speckle grains with an average size $\delta x = 65$ µm are detected by the photodiode array. In these conditions, the validity of equation (5) is established, and the spatial resolution of the detector is enough for processing the speckle pattern information. In figure 2, the double speckle pattern intensity for the case of a surface having an arithmetic roughness value $R_a = 12{\cdot}5$ µm is shown. In order to verify the system performance, Rugotest plane-ground comparison standards were employed with the following R_a roughness values: $1{\cdot}6$ µm, $3{\cdot}2$ µm, $6{\cdot}3$ µm, $12{\cdot}5$ µm and 25 µm. In figures 3, 4 and 5, the measured autocorrelation parameter W is plotted against the angular separation $\Delta\theta_1$ (expressed in arc min), for the roughness values $R_a = 3{\cdot}2$ µm, $6{\cdot}3$ µm and 25 µm, respectively. Finally, in figure 6, the autocorrelation value W measured for varying surface roughness is shown for a constant angular separation $\Delta\theta_1 = 30'$.

4. Conclusions

A speckle correlation method for the real-time measurement of surface roughness parameters is proposed. Two, non-interfering, partially correlated speckle patterns are simultaneously detected by a linear photodiode array. Their correlation degree depends on the surface roughness, and on the geometrical configuration of the optical system. From the speckle intensity autocorrelation, the roughness value of the surface is obtained. Some advantages of this method
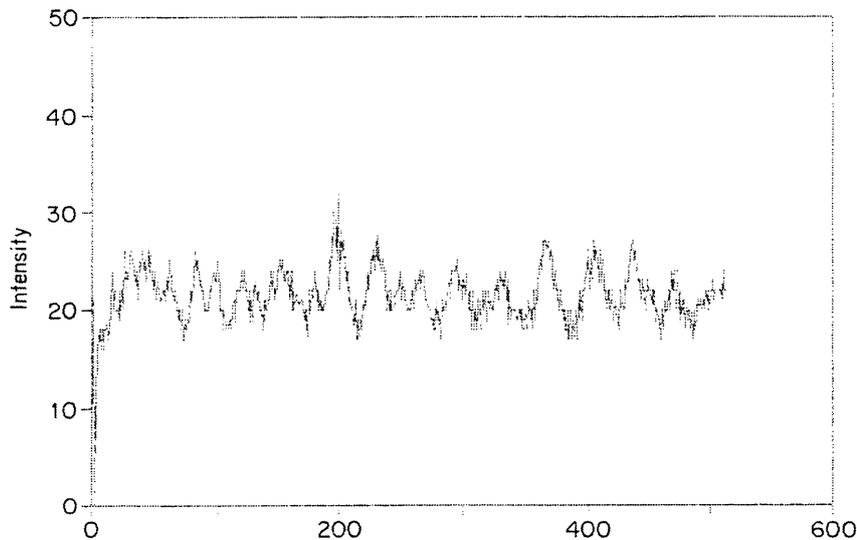

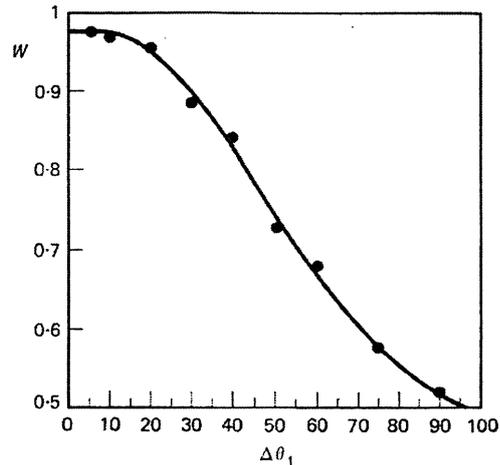Figure 2. Intensity distribution of a recorded double speckle pattern.

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Figure 3.   Normalized autocorrelation W measured for several values of $\Delta\theta_1$, for a surface roughness $R_a = 3.2$ μm.
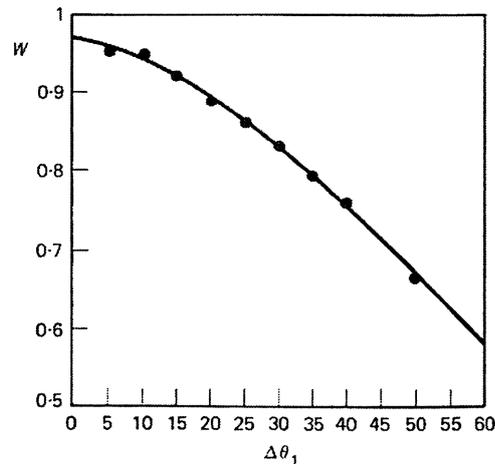

Figure 4.   Normalized autocorrelation W measured for several values of $\Delta\theta_1$, for a surface roughness $R_a = 6.3$ μm.

are: simple optical implementation which can be easily adapted for industrial applications, continuous real-time measuring capability up to about ten measurements per second, and low sensitivity to misalignments. The main disadvantage arises from the fact that a one-dimensional autocorrelation operation is performed (instead of a two-dimensional one), and hence, the signal-to-noise ratio obtained is not very high.

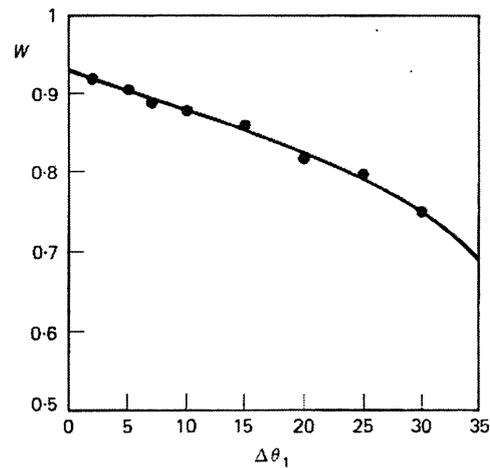Figure 5. Normalized autocorrelation W measured for several values of $\Delta\theta_1$, for a surface roughness $R_a = 25 \ \mu m$.
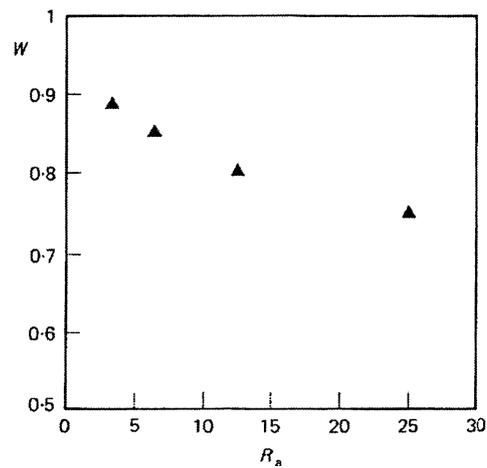

Figure 6. Normalized autocorrelation W against R_a for an angular separation $\Delta\theta_1 = 30'$.

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