AN INVESTIGATION OF LASER SPECKLE USING A LINEAR, CHARGE-COUPLED, PHOTODIODE ARRAY

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ABSTRACT

This thesis describes the use of a linear, charge-coupled, photodiode array, and microprocessor in the measurement of various laser speckle statistics.

Contrast and probability densities for fully and partially developed speckle patterns are derived theoretically as a function of scattering angle and surface roughness.

The experimental apparatus incorporating the photodiode array and microprocessor is described in detail, along with various experiments to check expected specifications. Using this apparatus, measurements are made of the probability density and contrast, as a function of scattering angle, for the speckle patterns produced by three different surfaces. From these results and the theoretical predictions the roughness parameters for these surfaces are determined.

In-plane surface displacement is measured using a cross-correlation technique and is found to produce accurate results over a wide range of displacements (from 1μm to 0.5mm).

A short section on speckle size is also included to verify theoretical predictions made in an earlier chapter.

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LIST OF SYMBOLS

Symbol	Meaning	Page where first mentioned
r	Surface roughness	2
w	Waviness	2
σ	Standard deviation of subscript	3
<>	Mean value of symbol within brackets	3
T	Correlation length	3
ϕ_i	Phase of ith elementary phasor	7
θ	Angle of incidence	7
ω	Angle of scatter	7
A_i	The ith elementary phasor	7
A	The resultant amplitude phasor	7
ψ	The resultant phase	7
λ	Wavelength of light source	8
$p()$	Probability density of symbol(s) within brackets	8
C	Speckle contrast	9
I	Speckle intensity (also relative intensity)	9
x, y	Real and imaginary components of the resultant amplitude phasor	10
n	The number of scattering centres	13
a	Amplitude of generalised phasor A_i	13
ξ	Smallest distance on a surface which produces a resolvable image in the speckle pattern	17
n'	Refractive index of air	17
d	Diameter of illuminated area on a surface	17
A_x, A_y	Amplitudes of the orthogonal components of partially polarized light	25
I_x, I_y	Intensities of the orthogonal components of partially polarized light	25
β	Angle between the net polarization vector ($\underset{\sim}{A}_T$) and $\underset{\sim}{A}_x$	27
α	Semi-angular subtense of the object at the speckle being observed	33
δ	Characteristic speckle size	33

L	Distance from the object to the speckle being observed	34
X,Y,Z,Q	Computer stack registers	77
M()	Signifies contents of memory locations within brackets	77
Mx	Particular memory space on computer (see Appendix B)	82
c	Compensated video data	84
f(I)	Frequency of occurrence for a particular intensity I	98
Δx	Speckle displacement	127
D	Object displacement	130
b	Light source to object distance	130
M	Micrometer displacement	130
r_c	A constant amplitude vector added to the random walk resultant amplitude	158

1 Introduction

When direct sunlight is observed after having been scattered from a slightly roughened surface, small multicoloured points of light, which appear to scintillate as the head or the surface is moved, will be seen. This phenomenon is an example of a speckle pattern caused by the scattered light forming a complex interference pattern in the space in front of the object.

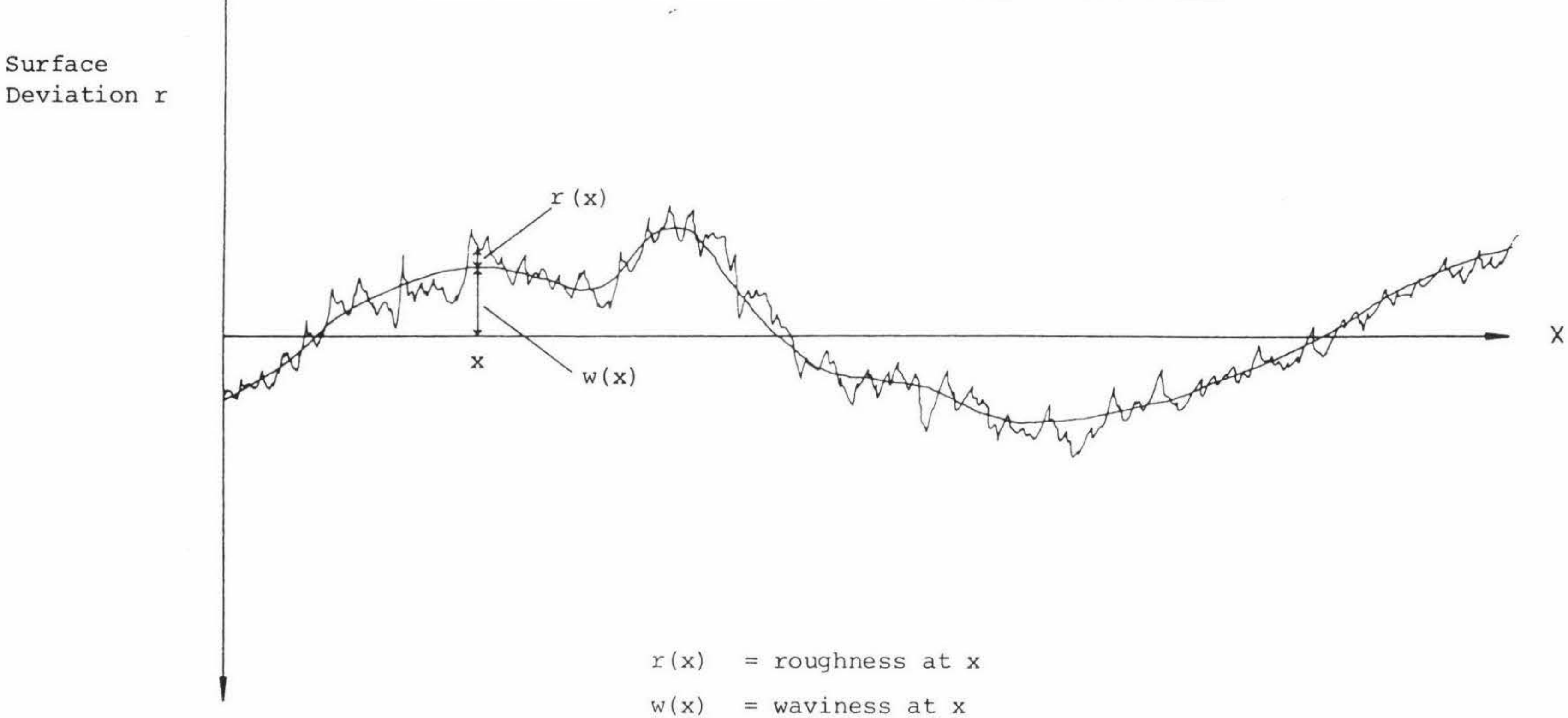
Most sources of light do not product an obvious speckle pattern due to their lack of temporal and spatial coherence. An incandescent lamp for example produces a speckle pattern which changes continuously with time, at such a rate that the eye perceives only a uniform illumination. The coherence of sunlight however, is sufficient to form speckles when scattered from very smooth surfaces having a roughness of similar order to the coherence length.

Before going any further it would be a good idea to clarify exactly what is meant by a rough surface, and to define a number of terms which will be used throughout the text. With reference to figure 1.1 it can be seen that for a two dimensional cross-section of a rough surface there are two components of surface texture.

(i) Roughness (or primary texture). These are the irregularities in the surface texture which result from the inherent action of the production process. (e.g. lapping, grinding, honing etc.)

(ii) Waviness (or secondary texture). The component of surface texture upon which the roughness is superimposed. Waviness may result from such factors as gross surface shape, (the object could be a cylinder for example), or from unintentional errors produced by faulty or imperfect manufacturing techniques.

Figure 1.1 Cross-section of a rough surface



Roughness and waviness may both be statistically defined in terms of their root mean square values. Because we can arbitrarily set their mean values to zero we have, using the relationship

$$\sigma_r^2 = \langle r^2 \rangle - \langle r \rangle^2, \qquad (1.1)$$

that $\sigma_r^2 = \langle r^2 \rangle$, (1.2)

where $\langle r \rangle$ is the mean value, $\langle r^2 \rangle$ the mean square value, and σ_r^2 the variance of surface roughness. The root mean square value of roughness is therefore simply equal to its standard deviation. In a similar manner we can also define waviness in terms of its standard deviation σ_w.

For most of this thesis it will be assumed for simplicity that $\sigma_w \ll \sigma_r$ although, for many real objects, this may not be the case.

In addition to these parameters we can also define a pseudo wavelength for such a surface in terms of its autocorrelation function. In the absence of any large scale waviness the autocorrelation function for a rough surface with a Gaussian probability density (a reasonable assumption for most randomly produced surfaces) will also be Gaussian in form, dropping from a maximum value at lag zero at a rate dependent on the adjacent peak-to-peak distance. We can numerically specify this rate by defining the correlation length T as the distance one must travel on the surface before the correlation coefficient has dropped by a factor of e^{-2}. The physical significance of this parameter can be seen more clearly in figures 1.2 and 1.3 which show two rough surfaces with the same surface roughness but quite different values of T.

Having defined the various aspects of a rough surface we will now move on to consider speckle patterns produced

Figure 1.2 Rough surface with small value of T

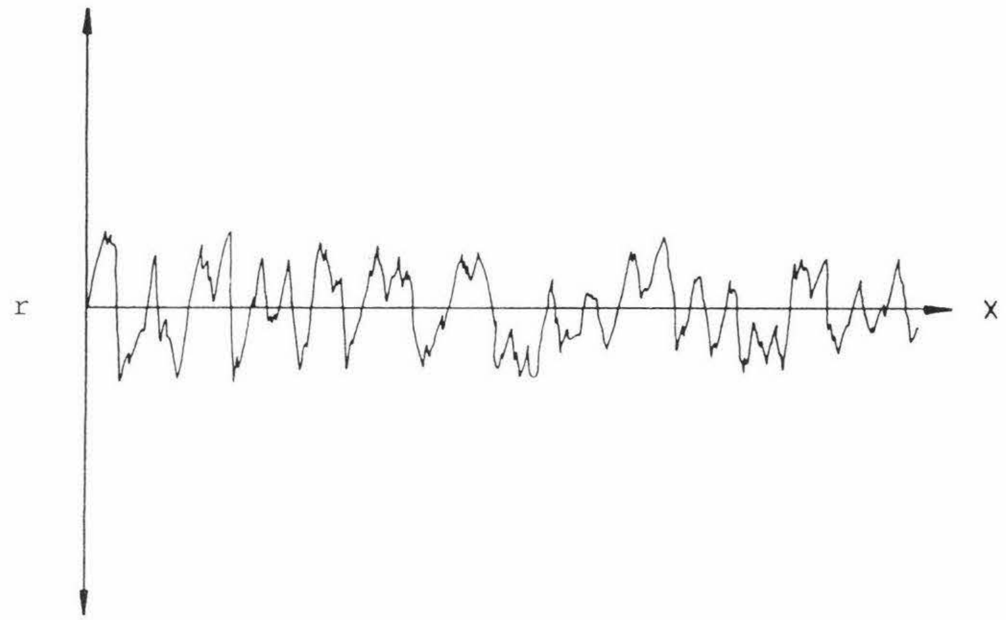
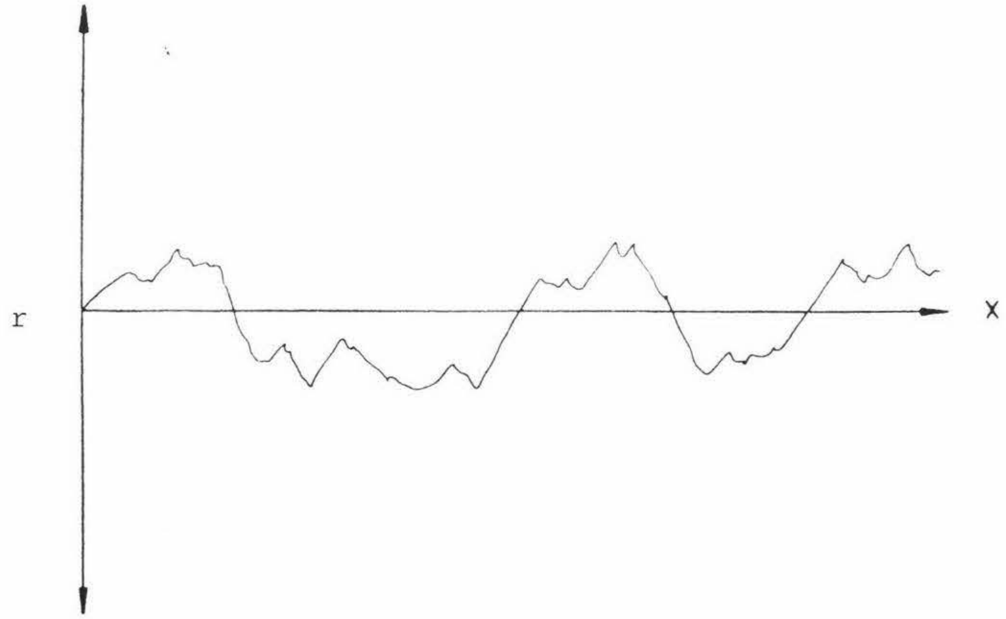


Figure 1.3 Rough surface with large value of T



using laser light. Because of its far greater temporal and spatial coherence the laser is an ideal light source with which to produce speckle. Practically any stationary object will produce a readily visible pattern, although surfaces such as milk or human skin will, because of their continuous movement (Brownian motion in the case of milk), tend to blur the speckles.

Surfaces with a roughness much less than the wavelength of light tend to produce a speckle pattern having reduced contrast and this fact will be used in this thesis to obtain a numerical estimate of σ_r, for various surfaces.

Another phenomenon which is immediately obvious when observing speckle is that for small displacements of an object (up to about a millimetre) the speckle pattern suffers little change other than a shift in the direction of the object's displacement. By measuring this shift, a non-contact means of measuring surface displacement can thus be obtained.

Most conventional work done with speckle has used photographic techniques which are often slow, or video processing which is usually complex and expensive. This thesis will present a new approach to the measurement of surface roughness and displacement by the statistical analysis of the speckle pattern as detected by a linear, charge-coupled, photodiode array.

While suffering from a number of statistical short comings (chiefly the limited number of sample points available) the array is quite sensitive and does allow rapid acquisition of data. In conjunction with a microprocessor and low powered laser it provides a reasonably compact system which, when perfected, could conceivably find its way into an industrial application.