Ain Shams University
Faculty of Science
Physics Department

APPLICATION OF SPECKLE INTERFEROMETRY TO THE STUDY OF FLUID FLOWS

A THESIS

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By

HATEM MAHMOUD HAMDY EL-GHANDOOR
M. Sc

Faculty of Science
Ain Shams University

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CONTENTS

SUMMARY

Speckle photography and speckle interferometry have been applied to the study of three different types of motion of light scattering objects, namely: uniform velocity, linear velocity profile, and a non linear velocity profile. The three types of motion are realized by lateral displacement of a rough surface, rotation of a rough surface, and a pipe flow of a fluid seeded with scattering particles.

Chapter I gives a survey of the formation of speckles and their characteristics. The methods of double and multiple exposure are discussed in their application to the displacement and movement of objects. Reconstruction analysis of the recorded speckle patterns by means of the formation of Young's interference fringes is described. This procedure has been applied to the lateral displacement of a rough surface and the rotational motion of the same surface. Since the center of rotation is not known from the specklegram, an analysis has been developed which allows for determining the angular velocity of the object from the measurement of the velocities at two arbitrary points on the rotating surface.

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CHAPTER I

APPLICATION OF SPECKLE PATTERN PHOTOGRAPHY TO SURFACE DISPLACEMENT AND ROTATION

I.1. Abstract

In this chapter, formation of speckles at the image plane and their characteristics are presented. These characteristics are summerized in the following points: 1) Size and shape of speckles, 2) Intensity distribution of speckles at the image plane, 3) Average contrast and surface roughness of the object, and 4) Density distribution of speckles per unit area and its dependence on surface roughness of the ground glass rough object.

Two beam interference fringes are ,formed resulting from the features on the rough object applying Zeiss - linik interference microscope. This serves in selecting the object of suitable surface roughness for speckle formation.

The speckles formed are used as a source for measuring surface displacement and rotation. Double exposure technique is performed by photographically recording the speckle pattern twice using a fine grain emulsion, before and after the object displacement. The two speckle patterns recorded are identical, but displaced. By examining the diffraction patterns of the recorded speckle intensity distribution, the displacement is measured.

Analysis of the doubly exposed plate is carried out by directing a narrow collimated coherent beam of light, emitted from a laser, onto the film record and measuring the spacing and direction of Young's fringes formed. In this method a point- by - point record of the variation of speckle pattern separation both in magnitude and direction, is build up. The accuracy achieved is 0.1 μm.

The double exposure technique has been applied to surface displacement measurement as a base for measuring surface rotation. Improvement in the technique has been achieved using ruby pulsed laser at λ = 6940 A^{o}. A modified method based on two points analysis that does not necessiate locating the center of rotation as a reference point, has been applied.

I.2. Formation of Speckles and its Characteristics.

I.2.1. Size and Shape of Speckles

When coherent light wavelets meet they interfere to form fringes. The most familiar example is Young's experiment in which the fringes are formed by the waves from two coherent point sources. When there are many point sources randomly distributed, the interference pattern formed no longer has any regularity. It takes the form of randomly distributed dark and bright spots of different sizes. These are the speckles. The introduction of lasers has brought many new applications to the speckle phenomenon. Laser speckles appear whenever an optically rough surface is illuminated with highly coherent light.

When an opaque surface is illuminated by a coherent source such as laser, the reflected wavelets coming from different points of the surface mutually interfere to form a volume of speckles in front of the surface. These are referred to as objective speckles or diffracted speckles. While their statistical properties remain the same for any surface which is optically rough, local speckle size and shape are functions of the surface texture and lens aperture.

The roughness of the surface needs to be of the order of few wavelengths of the light used. In Fig. (1) a transparent diffusive rough object is illuminated from the left by a coherent wave, converging to a focus in the neighbourhood of the point E. The roughness is assumed to be localized on the exit plane of the object. The irregularities in this plane are considered to act as a random set of positive and negative lenses[1]. The pencils of rays falling onto such lens elements are shown in Fig. (1). The rays marked with double arrows pass undeviated to the point E. The convex lens element at O_1, focuses rays at P_1, from which they diverge as a relatively narrow pencil, giving a wave W_1. The concave lens element at O_2 produces a pencil of rays coming from the virtual image P_2 which , because of the deeper curvature of the lens element, diverges at a wider angle pencil, giving the wave W_2. In the diffraction plane the total disturbance is the resultant of the mutual interference of the coherent waves produced by all such elements of the object. These waves have random mutual phases because of the random variation of the object thickness. At a point such as Q_1 light from all the elements of the object meet, whereas only those elements giving widerangle scattering send light to a point such as Q_2 further away from the center E of the pattern.

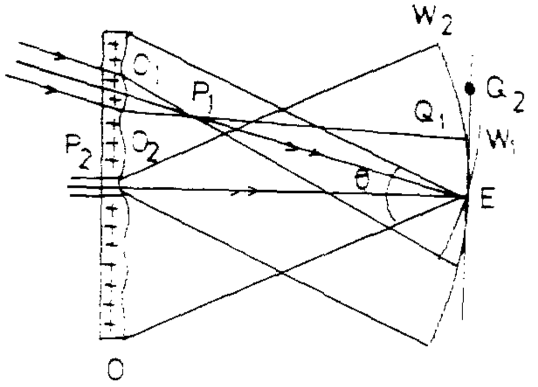

Fig.(1) Formation of Speckles in the Fraunhofer diffraction plane resulting from a transparent diffusive object.

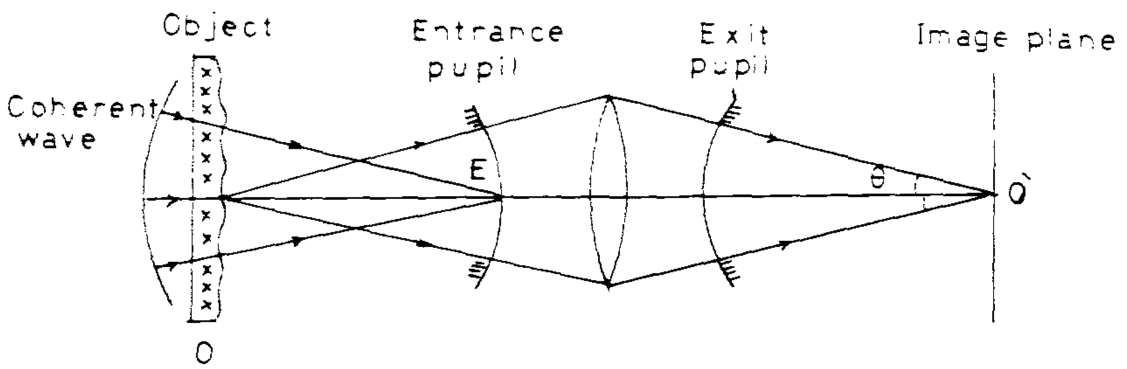

Fig.(2) Recording of Speckles at the image plane.

Since the maximum intensity that can be produced increases with the number of interfering waves, the envelope of the intensity in the diffraction pattern is expected to have a greater value at Q_1 than at Q_2. Thus, if the size deviation of scattering elements relative to the mean value exhibits a Gaussian distribution, the envelope of the diffraction pattern is expected to have a maximum at the center E and to decrease continously towards the edge. The form of this distribution depends on the standard deviation of the sizes and curvatures of the elements. If all elements were of the same size and curvature the scattered waves would have the same angular spread, and there would be a large constant envelope of intensity, with a rapid decrease to zero at the edge. The greater the variation in size of the surface elements, the greater is the angular range of scattering produced.

For recording speckling in the image plane of a rough surface using coherent light, the entrance pupil is illuminated by a speckled diffraction pattern, as shown in Fig. (2).

This random variation of illumination, then appears in the exit pupil, so that the formation of speckles termed speckling in the image is determined by considering the exist pupil to act as a rough object.

The order of size of speckling in the image is thus determined by the formula λ / θ_c, where θ_c is the total convergence angle in radians of the image forming lens, and λ is the wavelength of the coherent light source.

The speckle size or shape can be altered by changing the size or shape of the lens aperture. Thus speckles are no longer regarded merely as a noise element, but as a carrier of information to be used in different applications. This offers a powerful and simple tool for studying surface roughness and for measuring displacement and for strain analysis.

To get subjective speckles at the image plane, a transparent object such as ground glass, is illuminated by a collimated laser beam. A lens L, forms the image of this object at the image plane (Fig.(3)). All points on the object scatter coherent light waves that are capable of interfering. The speckle is caused now by interference in the image plane between the waves scattered from the different points on the object.

The image formed, is the result of the superposition of the amplitudes of diffraction patterns due to different points on the object taking into consideration the phase variations due to the thickness variation of the

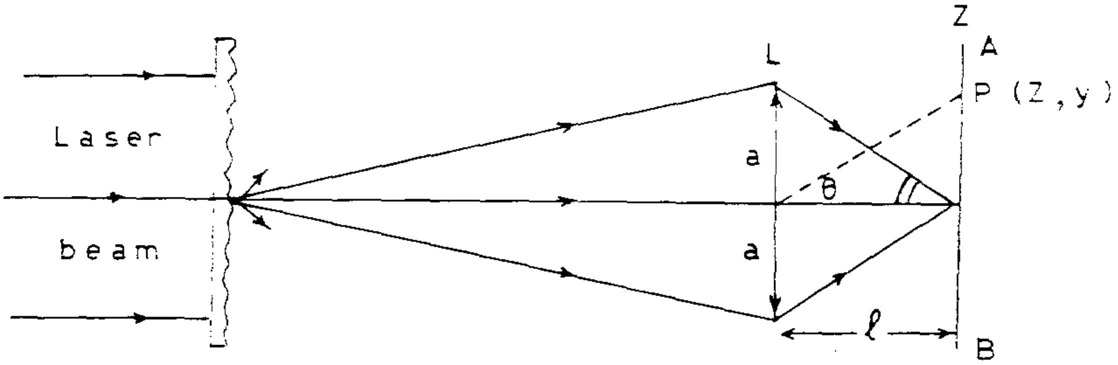

Fig.(3) Formation of subjective speckles.

ground glass.

The smallest speckle spots have diameters that are of the order of magnitude of the diffraction pattern of the image forming lens. For a lens of circular aperture with a diameter 2a, the amplitude in the image plane AB, is given by the Fourier-Transform of a circular surface. The amplitude f (θ), at any point P in the image plane determined by the angle θ, is

$$f(\theta) = \frac{2 J_1 (Z)}{Z} \qquad \text{.........(1)}$$

Where $J_1(Z)$ is the Bessel function of order one of the variable Z.

The diffraction image or Airy disk consists of a very luminous spot, surrounded by alternating dark and bright rings. Fig. (4) shows the variation of amplitude $f(\theta)$ and Fig. (5) the variation of intensity $I = f(\theta)^2$ as a function of Z. The intensities of the luminous rings are much smaller than that of the central spot, they decrease rapidly.

For the first dark ring the table of the Bessel function gives Z = 3.83, then the angular radius of the first dark ring is

$$\theta_1 = Z/Ka \qquad \text{.........(2)}$$