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Preface

The ICTP-LAMP internal reports consist of manuscripts relevant to seminars and discussions held at ICTP in the field of Laser, Atomic and Molecular Physics (LAMP).

These reports aim at informing LAMP researchers on the activity carried out at ICTP in their field of interest, with the specific purpose of stimulating scientific contacts and collaboration of physicists from Third World Countries.

ABSTRACT

Surface deformations of rigid bodies produced by thermal as well as mechanical strains have been investigated using double-exposure holographic interferometry. The recorded interference fringes have been discussed qualitatively.

INTRODUCTION

Interferometry stands for the comparison of two wavefronts by means of the study of their interference pattern. The shape of interfering wavefronts, their mutual orientations, and also the spectral composition of the radiation and the angular dimensions of the light sources affect the form of the interference pattern. By investigating the distribution of the intensity in an interference pattern one can determine the spectral composition of the radiation or the angular dimensions of the source. On the other side, by studying the displacements in space of the interference pattern, it is also possible to obtain the difference between the frequences of the interfering waves. All these investigations are carried out with optical interferometry.Holographic interferometry, developed on the basis of optical interferometry, indicates, however, that one or both of the waves under comparison are generated by holograms. This implies some very significant advantages over the conventional optical interferometry such as the possibility to compare extremely complicated wavefronts and record small differences between them. In holographic interferometry, it is also accessible to produce interference between two wavefronts which did not exist at the same time.

Holography is a technique of recording and reconstructing waves that is based on recording the distribution of the intensity in an interference pattern formed by an object wave and a reference wave. The record, formed in photosensitive material of the photographic plate, is called a hologram. Wavefront reconstruction takes place, in a second step, when the hologram is illuminated with the reference wave.

Because a hologram is an interference pattern formed by an object wave and a reference wave the complex amplitudes of these waves in the plane of the holographic plate can be written as

$$A_o = a_o \exp(i\phi_o) \quad (1)$$

and

$$A_R = a_R \exp(i\phi_R) \quad (2)$$

where a_o and a_R, ϕ_o and ϕ_R are the amplitudes and phases of the object and reference waves, respectively.

If these waves are coherent, the interference of them on the plate creates interference pattern in which the distribution of the illumination is given by

$$I = |A_o + A_R|^2 = a_o^2 + a_R^2 + A_o A_R^* + A_o^* A_R \quad (3)$$

It is obvious from eq. (3) that the intensity at any point in the interference pattern is the sum of the intensities of the individual waves and the interference terms which include the relative phase information.

On the other hand, assuming a linear relation between the transmittance of the completed hologram, T, and the exposure time, t, the properties of the photographic plate can be related to the sum of the intensities, which is a straight line given by

$$T = kIt \quad (4)$$

where k is a coefficient giving the slope of the straight section of the characteristic curve [1].

Combining the eqs.(3) and (4) one obtains the distribution of the amplitude transmittance of the hologram:

$$T = kt(a_o^2 + a_R^2) + ktA_o A_R^* + ktA_o^* A_R \quad (5)$$

The illumination of the hologram with the reference wave yields the following distribution of the complex amplitudes:

$$TA_R = (kt(a_O^2 + a_R^2))A_R + kta_R^2 A_O + ktA_R^2 A_O^* \qquad (6)$$

The first term in the right-hand side of eq.(6) represents the zero-order wave. The second term describes the object wave reconstructed by the hologram which corresponds to a wave of the +1st order forming a virtual three-dimensional image of the object at the same place where the object was during recording the hologram. The third term gives the conjugate to the object wave corresponding to a wave of the -1st order which describes a distorted real image of the object. To obtain an undistorted real image, the hologram has to be illuminated with a wave that is the conjugate to the reference wave. Thus, the reference beam should be accurately retroreflected so that all rays of the reflected beam are opposite to the original reference.

Qualitative as well as quantitative investigations of the interference pattern (fringe) obtained in this fashion deliver revealing information about the deformation, vibration, displacement, changes of refractive index, surface structure and material defect of the test object. In the last years, a number of experiments utilizing the holographic interferometry has been performed to measure displacements and deformations in solids [1,2] as well as for flow diagnostics in fluids [3]. Various experimental techniques [4,5] and mathematical approaches [6] for quantitative analysis and interpretation of friges have already been developed. Recently digital image processing techniques have been applied to moire detection of flows [7].

In this work, using the double exposure holographic interferometry we demonstrated experiments of surface displacements produced by thermal and mechanical stresses that allow detection of material defects and strain analyses.

METHOD

The double-exposure technique of the time lapse interferometry [8] involves to record two holograms, one of the object in its undisturbed state and the other of the object in some disturbed state. In the reconstruction process, the two recorded wavefronts interfere with each other to produce a fringe pattern wherein the contour and spacing describe the changes that occured between the two exposures. Illumination of the doubly exposed hologram not only results in the simultaneous reconstruction of two waves but also causes them to interfere under ideal conditions. The waves can share the diffraction efficiency [9] of the hologram equally resulting in equal intensity for both waves.

The double-exposure method obviates some experimental difficulties of the real-time interferometry, which is also successfully applied to rigid body strain analyses, but demands great accuracy of the optical setup. The real-time holographic interferometry also makes use of recording one exposure to the initial state of the test object and a second exposure to its changed state. The hologram of the initial state, after being developed, is put in exactly the same place where it was at the moment of the first exposure. If changes occur in the test object the second exposure is made. In the double-exposure holograms distortions due to emulsion shrinkage are extensively eliminated resulting in high-quality fringe contrast compared to that obtainable with the real time procedure.

EXPERIMENTS

In order to detect the surface deformations produced by thermal as well as mechanical strains we set up a simple optical arrangement as shown in Fig. 1. The system was mounted on a vibrationlly isolated table of marble blocks sitting on inflated bicycle tubes.

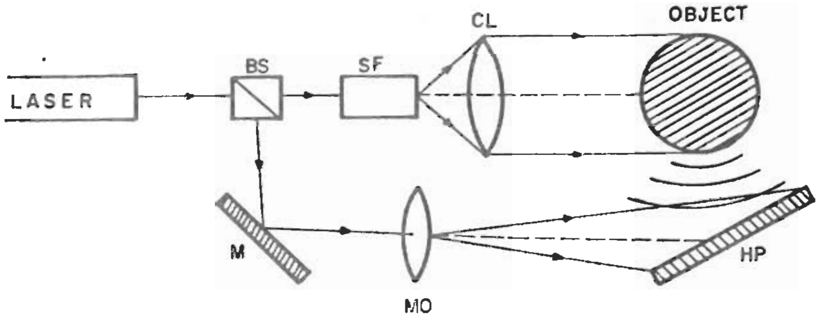

Fig.1. Schematic diagram of the setup used for investigations of surface deformations. BS-Beam splitter; SF-Spatial filter; CL-Collimating lens; M-Mirror; MO-Microscope objective; HP-Holographic plate.

The experiments of temperature displacement was carried out on a object consisting of two identical porcelain-resistors connected in parallel. The object's deformation was produced by current junction of the resistors. The temperature on the resistors was controlled by measuring the current in each resistor. To record holograms of the thermal expansions with the double exposure method the first exposure was made at room temperature. For the second exposure the object was heated about 5 minutes several degrees above the room temperature. After having been reached uniform equilibrium temperature the second exposure was made on the same holographic plate. Fig.2 shows a typical photo-

graphic recording of a holographically reconstructed virtual image produced by this fashion.

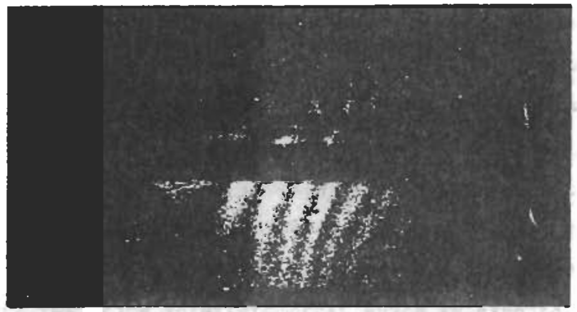

Fig.2. Photographic recording of holographically reconstructed virtual images of identical porcelain resistors.

For recording mechanical deformations, we used as test objects a brass cylinder 10-mm in diameter and 100-mm in length and an aluminium plate in dimensions of 20-mm x 100-mm x 2-mm which were polished flat and rigidly fixed in their holders. The required surface deformations were given the objects by submitting to appropriate forces axially to the brass cylinder and vertically to the aluminium plate surface. Typical photographic recordings of their reconstructed virtual images are illustrated in Fig.3 and 4.

Fig.3. Photographic recording of the virtual image of the brass cylinder. The fringes observed illustrate a combined effect of the linear variation of the sensitivity and displacement vectors resulting in curved and unequally spaced fringes.

In all experiments the exposure time for both illuminations was the same as determined by several test exposures by measuring the net power of laser light transferred to the surface of the recording material. The optimum reference-to-object beam ratio was found in the region of 5:1 to 8:1. All holograms were recorded on 4 inches x 5 inches Kodak 649F plates. The process of developing and bleaching of the holograms was carried out as follows: The exposed plate was developed in Kodak Developer D-19 or in a homemade developer for about 5 min at room temperature and rinsed immediately in water for 30-40 sec. In the second step, the plate was fixed in Kodak Rapid Fixer bath for up to 6 min and washed in flowing water for about 5 min. Then the plate was bleached and subsequently washed again in flowing water. Finally the hologram was dried in a dust-free cabin until the emulsion became hard. Similar techniques of development and bleaching are given in literature [8,9].

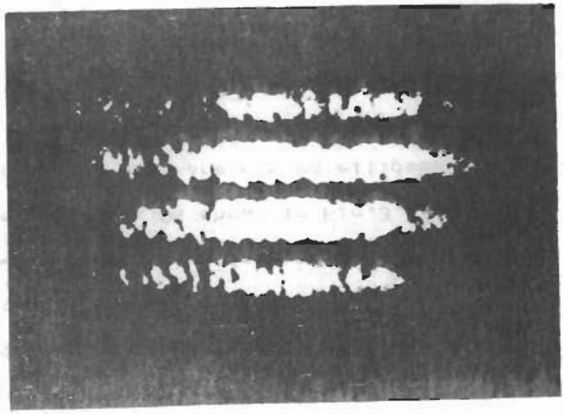

Fig.4. Photographic recording of the virtual image of the aluminum plate. The object with plane surfaces is seen covered by a pattern of parallel equally spaced fringes.

DISCUSSION

It is assumed, that, if the internal temperature of an isotropic body is increased slightly, all the infinitesimal line elements in the volume of the body should undergo equal expansion maintaining their initial directions. In this assumption, the normal strain components due to temperature change should depend only on the coefficient of thermal expansion and the amount of the temperature change. On the other hand, when heat is propagated through a solid material, in the recording process the fringes exhibit the propagation of the heat as the solid expands. If the material is internally damaged, the heat will not travel uniformly. Thus the fringes will indicate material defects that are not noticeable by simple inspection. Comparing the fringes both of the holographically reconstructed images of the identical porcelain resistors shown in Fig.2 it becomes obvious that the fringe patterns are slightly different. Curved fringes appear on both objects with different distances and slightly displaced positions though the geometry of recording and reconstruction was identical for both objects. This should be referred to not identical material composition of the test resistors.

Fig.3 demonstrates the mechanical stresses on the brass cylinder which shows obviously large rigid body displacement caused by applied force axial to the test object. As it is assumed in the fringe-vector theory [see, e.g., 6] of holographic strain analysis this results in curved and unequally spaced fringes formed along the lines of intersection of the object with the fringe-locus surfaces. This becomes obvious when we note that the fringe-locus surfaces intersect the top of the cylinder. As shown in Fig.3, it results in fringes seen on the object that are closed ellipses instead of being just curved lines. The fringes observed exhibit a combined effect of linear variations of the sensitivity and displacement vectors. For a more detailed fringe interpretation theoretical predictions based on the fringe-vector theory should be made, which delivers average values of the computed strains.

The aluminum plate submitted to the force perpendicular to its surface gives, as expected, the image crossed by horizontal fringes which represent a contour of out-of-plane deformation (Fig.4). The fringes seen on the test object appear along the lines of intersection of the object's surface with a set of parallel equally spaced fringe-locus planes. In this type of deformations generated by applying a force through a cylinder-shaped rigid body results in a pattern of fringes that would appear to be created along the lines of intersection of the object's surface with a set of parallel equally spaced planes.

REFERENCES

1. Schumann,W. and Dubas,M., Holographic Interferometry (Springer Verlag, Berlin, 1979).
2. Hariharan,P., Optical Interferometry (Academic Press, Sydney,1985).
3. Trolinger,J.D. and Simpson,G.D., Opt. Eng.18, 161, 1979.
4. Pryputniewicz,R.J. and Bowley,W.W., Appl. Opt. 17(11), 1748, 1978.
5. Paoletti,D. and D'Altorio,A., Opt. Commun. 50(6), 338, 1984.
6. Stetson,K.A., Opt. Soc. Am. 64(1), 1, 1974.
7. Youren,X., Vest,C.M., and Delp,E.J., Opt. Lett. 8(8), 452, 1983.
8. Collier,R.J., Burckhardt,C.B., and Lin,L.H., Optical Holography (Academic Press, New York, 1972).
9. Smith,H.M. (ed.), Holographic Recording Materials (Springer Verlag, Berlin, 1977).