HOLOGRAPHY FOR FAST REACTOR INSPECTION

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ABSTRACT

Holography, an optical process whereby an image of the original subject can be reconstructed in three dimensions, is being developed for use as an optical inspection tool. With a potential information storage density of 10^{16} bits/m^2, the ability to reconstruct in 3 dimensions, a depth of field of up to 8 metres, extremely wide angle of view, and potentially diffraction limited resolution, holography should be invaluable for the optical recording of fast reactors during construction, and the inspection of optically accessible regions during operation, or maintenance down-times. The photographic emulsions used for high resolution holography are fine-grained and fog only very slowly when subjected to γ-radiation, so that inspection of highly radio-active regions and components can be effected satisfactorily. Some of the practical limitations affecting holography are described and ways of overcoming them discussed. Some preliminary results are presented.

INTRODUCTION

In the 20 years since the development of the laser transformed holography from a barely realisable curiosity into an exciting practical proposition, the subject has demonstrated enormous potential and has been widely employed, in the laboratory, to tackle an enormous range of problems. In the field of practical engineering, however, applications have been very limited, and have consisted almost entirely of the use of double-exposure holography as a means of recording distortion of structures or changes in refractive index of a medium (1). The straightforward use of holography to provide high resolution three dimensional records of engineering structures has been neglected - and given the poor quality of most of the published reconstructions of holographically recorded scenes, this is perhaps not surprising.

Superficially holography has much to offer as a replacement for photographic or photogrammetric recording of important features of structures. The ultimate resolution, rarely achieved in practice, of a scene recorded photographically is set by the lens aperture, that of a hologram by the plate size. For equal diameter of lens and holographic plate, the resolution limit is the same:-

$$N = \frac{a}{1.22\,\lambda D} \quad \text{line pairs/mm resolved at distance D for light of wavelength } \lambda. \qquad (1)$$

Since large diameter holographic plates are cheaper and easier to obtain than diffraction limited lenses, the potential resolution of a hologram is usually greater than that of a photograph, but this advantage can only be realised if the real pseudoscopic image is studied in reconstruction. More startling however, is the difference in information storage capacity of the two media. The information stored on a photograph can be approximated to the total number of discernible image points. Thus for a negative of area A on which N line pairs per mm can be resolved, the number of information points is given by:

$$I_p = n^2 A \qquad (2)$$

and using the high figure of n = 100 line pairs/mm, we obtain a figure for the information stored on a conventional negative of $I_p \leq 10^{10}$/m^2.

On the other hand for the hologram no part of the image is embodied in any single point in the hologram. The information storage here is limited by the physical size of light sensitive grains embedded in the emulsion. Assuming that the emulsion contains the equivalent of a single continuous layer of light sensitive grains, the number of bits of information contained in the hologram will be:

$$I_H = \left(\frac{1}{\ell}\right)^2 A \qquad (3)$$

Where ℓ is the linear dimension of the photographic grains. Using $\ell \simeq 30$ nm, we obtain $I_H \simeq 9\times10^{14}$/m^2. Thus a single hologram can provide the information contained in many thousands of photographs, particularly since a hologram of 300 x 400 mm may well be taken instead of a photographic negative 60 x 60 mm in size.

With the ever growing demands on safety aspects of all types of nuclear plant and the implications of these trends for fast reactor construction and inspection requirements, the apparent advantages of holography for optical recording deserve further study, and this paper describes some of the work now in progress at the Marchwood Engineering Laboratories. Particular attention is being paid to those factors of laser and holo-camera design which limit resolution, the problems of stability and reliability, and techniques for examining and recording the reconstructed image. A holo-camera is also being developed for the useful but less demanding application of double pulse holography for the study of dynamic characteristics of reactor structures, and possible fault detection.

FACTORS AFFECTING RESOLUTION

Figure 1 illustrates the process of recording and reconstructing a hologram. In construction, the light scattered from the subject and the reference beam must be coherent over times at least equal to 2D/C where D is the depth of the illuminated scene, C the velocity of light. The resulting interference fringes formed in the emulsion (shown diagrammatically in Figure 1 for one point on the subject) should be faithfully recorded with the correct intensitydensity (gamma) factor. The reference beam should be an ideal, diffraction limited, point source, and the beam used to illustrate the subject should preferably be an unblemished plane or spherical wave. The spacing and relative position of the source, subject, holographic plate and any optical components of the holo-camera must be stable to better than $\lambda/2$ for the duration of the experiment. Finally the recording material (photographic emulsion) should remain undistorted by chemical processing, except to produce the desired fringes. Changes in lateral emulsion dimension appear to be small, but shrinkage through the 10 to 15 μm thick emulsion can alter the fringe angles, producing a significant spherical aberration.

In reconstruction, to obtain a pseudoscopic image, a diffraction limited beam is required propagating in the opposite direction to that used to construct the hologram. Some errors must inevitably arise here due to the relatively poor quality of the glass backing plate. The holographic plate should be at the same position relative to the point of convergence of the reference beam as during construction, at the same angle to it and the wave-length of the reconstructing beam should be the same as that used for construction - a requirement not normally met if pulsed lasers are used.

The factors requiring attention, and some comments on the effects are as follows:-

Coherence

Coherence can be divided into temporal (along the wave train) and spatial (across the wave front). Temporal coherence is necessary to give depth to the hologram - and in our work the required depths range from 8 m downwards. Output and intra-cavity etalons are used to provide a single longitudinal mode of oscillation. c.w. lasers with bandwidths of $\sim$ 1 MHz are commercially available and pulsed ruby lasers are manufactured which operate in single longitudinal mode with moderate reliability. When the laser operates in two modes "contouring" of the subject occurs due to "beating" of the two modes at intervals $\ell = \lambda^2/\Delta\lambda$ where $\Delta\lambda$ is the wavelength difference. This results in loss of illumination of the subject at the regular intervals ℓ. For our application with pulsed lasers, a very high degree of reliability must be obtainable, in industrial conditions, with lasers operated by non-specialist staff. We are presently studying the factors which cause a change from single to two-mode oscillation in pulsed ruby laser oscillator amplifier systems.

Beam Quality

A spatially coherent TEM_{oo} beam satisfies the requirements for reference and illuminating beams, and again this is normally available from commercial c.w. lasers by a combination of oscillator designs and beam spatial filters. An additional requirement not always met in c.w. lasers is beam pointing stability commensurate with diffraction limited beam divergence. Consideration of Figure 1 shows that the size of a resolvable point on the subject is determined by the angular size of the laser source. Thus if the laser produces a beam with an apparent source size S at distance R from the centre of the holographic plate, the smallest possible resolvable size on a point of the subject distance D from the centre of the holographic plate will be:

$$P \simeq \frac{SD}{R} \qquad (4)$$

Although single transverse mode operation of single stage pulsed ruby lasers working at lower power ($\lesssim$ 50 mJ) is relatively easily obtained, and a clean beam profile can subsequently be obtained by the usual spatial filtering technique, the performance of multi stage oscillator amplifier system has generally been unsatisfactory hitherto because of the difficulty of spatially filtering the high power output without producing air breakdown in the small filtering aperture.

However, subsequent to experimental work we have recently had a 10 joule 'Q' switched holographic laser constructed (Figure 2). This has been designed jointly with J.K. Lasers Ltd. Our technique for cleaning up the beam has been to spatially filter the output from the oscillator, before passing into the amplifiers. By careful choice of the focal length of the spatial filter lens and pinhole diameter the spot is kept at a size above that at which air breakdown will occur. The filter diameter is designed to pass the central mode of the focussed Airey disc of a diffraction limited TEM_{oo} beam. A second lens recollimates the beam leaving some residual divergence so that the distance between the apparent laser source and the first amplifier places the amplifier in the farfield of the source.

Processing

Clearly processing of the hologram is of prime importance in ensuring good quality holography. This is a subject on which Phillips has made major contributions (3), and reference should be made to this author's work.

Stability

Stability requirements for our work are such that we consider the use of c.w. lasers to be out of the question. A laser pulse length of $\sim$ 100 ns is so short that any mechanical structure which is not undergoing very high amplitude oscillations cannot move through a distance of $\lambda/2$ during the pulse unless it is subjected to mechanical forces which will cause the structure to disintegrate. The stability problem is then one of ensuring that a standard of engineering is employed such as to reduce long term movements of components relative to each other to an acceptable level. For routine industrial use this requirement is a demanding one, and a substantial effort is being devoted to it. In our experience the design of the laser bed, the physical stability of the components particularly the etalons contained in the oscillator, and the effects of changes in ambient temperature all merit urgent attention if robust holocameras are to be developed.

Holocamera Physical Dimensions

A small change in the distance R between the apparent laser source Q (Figure 1) and the holographic plate will produce a change in the distance D between the point T on the subject and the holographic plate given by:-

$$\delta D \approx -\frac{D}{R}\,\delta R \qquad (5)$$

Thus if accurate measurements of dimensions are required on large structures the position of Q must be fixed relative to the holographic plate to the same order. If separate recording and reconstruction equipment are to be used, the distances must be equal in the two pieces of equipment to the same order. Any difference in these dimensions will also introduce 'spherical' aberrations, which will be severe for large numerical apertures.

A change in angle of the hologram to the reference beam will introduce aberrations. However a reasonably secure mount will introduce less error than that produced by changes in replay wavelength, discussed later, and will not be considered here. Good quality mounts should be employed to provide vibration free mounting of the plate. It should be possible to return the plate to its original mounting position within a fraction of a wavelength.

Optical Components

In principle the holographic process depends upon the interference of two coherent wavetrains of arbitrary form, and reconstruction requires simply that the reference beam have the same arbitrary form for both construction and reconstruction. Therefore, optical components of any quality can be used, provided they are used in precisely the same position and orientation for both construction and reconstruction. In practice it is probably easier and certainly safer, to use diffraction limited optics throughout.

Change of Wavelength

Holograms obtained using a pulsed ruby laser cannot readily be reconstructed in light of the same wavelength, and it is usual to use He-Ne light for this purpose. It is worthwhile, therefore, devoting some time to consideration of the effects of wavelength change on the performance of a hologram, in the absence of other distorting influences, and especially of changes in dimension of the emulsion.

Referring to Figure 3(a), consider only effects in the plane perpendicular to the holographic plate which includes both the reference beam source and a point P on the reconstructed subject. AB is the holographic plate, length 2a with centre point O. OP is defined by (r, θ_o), AP by (s, θ_1) BP by (t, θ_2). The reference beam is taken to be parallel, and at angle ϕ to AB. When the hologram was constructed fringes formed in the emulsion at points on the holographic plate so as to bisect the angle between the reference beam and the lines AP, OP, BT etc, these being the fringes relating solely to point P.

The spacing between successive fringes at each point on the emulsion is given by (Figure 3(b))

$$d = \lambda \sin \frac{\pi-(\theta+\phi)}{2} \qquad (6)$$

where θ refers to the angle between the holographic plate and a line to point P from an arbitrary position on AB.

When the light wavelength λ is changed to $\lambda+\delta\lambda$, equation (6) can only be satisfied by a change in the angle ϕ of the plate to the reference beam to $\phi+\delta\phi$ if θ is constant at all points - i.e. if P is infinitely distant, or AB is infinitesimal. Adjustment of ϕ must therefore be to some optimum value $\phi+\delta\phi$ corresponding to complete correction at, say, point O. This failure should not affect resolution, but will affect diffraction efficiency.

The point P will be reconstructed at P when a reversed reference beam of wavelength λ is employed for reconstruction. If a wavelength $\lambda+\delta\lambda$ is employed, and the angle ϕ adjusted $\phi+\delta\phi$ to match the fringe spacing the rays AP, OP, BP will each be rotated by angle $\delta\phi$ such that $(\lambda+\delta\lambda)\sin\frac{(\pi-\theta-\phi_o-\delta\phi)}{2} = \lambda\sin\frac{(\pi-\theta-\phi_o)}{2}$.

Approximating $\cos\delta\phi \approx 1$, $\sin\delta\phi \approx \delta\phi$ and ignoring 2nd order terms

$$\delta\lambda \;\sin\frac{(\pi-\theta-\phi_o)}{2} - (\lambda)\cos\frac{(\pi-\theta-\phi_o)}{2} = 0$$

$$\frac{d\phi_o}{d\lambda} = \frac{1}{\lambda}\tan\frac{(\pi-\theta-\phi_o)}{2} \qquad (7)$$

Equation (7) defines the angular movement of rays AP, OP and BP. The points P', P", P'" to which bundles of rays from each of these regions will converge will therefore be moved from P by distances $s\delta\phi$, $r\delta\phi$ and $t\delta\phi$. The spread of these values gives a measure of the consequent blurring of point P. The blurring can be expressed as the ratio of the "chromatic" to the diffraction blurring. At any given value of $r/a, \theta_o$ and ϕ this chromatic blurring factor can be expressed in terms of a constant multiplied by $(r\;\delta\lambda/\lambda^2)$. Thus values of $(r\;\delta\lambda/\lambda^2)_{lim} = 1/C$ define values of this expression for which the chromatic blur is the same size as the diffraction blur. Figure 4 shows how this quantity varies as a function of the holographic aperture r/a and the angle of the reference beam to the holographic plate for the special case $\theta_o = \pi/2$. Figure 5 illustrates the effect of change in the position of P (defined by the angle θ_o, and the holographic aperture r/a) at a fixed reference beam angle ϕ. Values of $(r\;\delta\lambda/\lambda^2)_{lim}$ in Figure 5 have been calculated for the $\delta\phi$ which gives brightest reconstruction of the point P.

It is apparent from Figures 4 and 5 that the chromatic blurring resulting when He-Ne light is used to reconstruct a hologram made in ruby light, is important especially at peripheral points in the scene and at low reference beam angles. Values of r_{lim} for the case of a hologram recorded with ruby light, and replayed in He-Ne light are shown in Figures 4 and 5. For $\phi = 10$, $\theta = \pi/2$ the chromatic blurring will be 100 times diffraction limited at 150 mm from a 150 mm diameter hologram, but only ten times the diffraction at 1.5 m from a 300 mm diameter plate. For these reasons we have purchased a tunable c.w. laser for holographic reconstruction. The very severe blurring at low numerical aperture and small values of θ_o may still be a limiting factor in hologram performance, since the same effects are to be expected from changes in the thickness of the emulsion during processing.

EXAMINING AND RECORDING THE RECONSTRUCTED IMAGE

This is not the place to discuss techniques of producing pseudoscopic 'real' images (4). It is sufficient to say that a 'real' pseudoscopic image of the same size and dimensions as the original subject can be holographically produced, projected in three dimensional space, Figure 1. It is called pseudoscopic because it faces the holographic plate and is seen as 'inside out' by the observer. As stated above such real images must be employed if the potential resolving power of a holograph is to be realised. Extremely fine grain photographic materials can be located in the projected image carefully positioned in the actual plane of focus of the detail required. Figures 6(a) (b), (c) and (d), which are reproduced here, were obtained by this method. Alternatively, any desirable degree of magnification can be achieved by employing some optical device such as a microscope or macro camera, to record those portions of the image required for detailed examination. Figure 7 taken from a real image reconstruction of a 1000 lines per inch (40 µm square) mesh was produced in this way.

DOUBLE-PULSE HOLOGRAPHY

If a subject is recorded holographically, displaced or distorted through distances of a few wavelengths of the light used for the recording, and then recorded again on the same plate, the resulting composite hologram will, when reconstructed, exhibit an interference pattern caused by interaction between the two sets of reconstructed wavefronts, so that the movement between the two exposures can be quantified in all three dimensions limited only by the range of views of the subject recorded on the hologram. This "double pulse" holography has been widely used for studying static and dynamic distortions of a wide range of engineering structures, and has the advantage that it is much less demanding, in terms of beam quality, than the type of high resolution work discussed above.

APPLICATIONS TO FAST REACTORS

The combination of high resolving power, large field of view, great depth of field and information storage capacity makes holography a potentially powerful tool for the optical inspection of fast reactors. By taking "record" holograms of reactors under construction a quantity of information equivalent to many thousands of photographs can be obtained and made available to engineers at any time during the operating life of the reactor, giving a three dimensional realism to the record which is unattainable in any other way. Inspection of optically remote areas of the reactor can be achieved, even in high radiation fields (> 10^5 Rads/hr) by holographic recording using a pulsed laser, and the record inspected in fine detail in the laboratory, as illustrated in Figure 8, using the pseudoscopic real image. The additional advantage of the holographic real image, that it readily allows "sectional" views of cylindrical objects to be obtained (see Figure 6) is also likely to prove invaluable.

The limitations of double-pulse holography for studying dynamic and static distortions, and for detecting sub-surface flaws are also being investigated.

ACKNOWLEDGEMENT

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(3) PHILLIPS, N.J., CULLEN, R., WARD, A., PORTER, D. Proc SPSE, May 1978, Boston, Mass.
(4) SMITH, H.M. Principles of Holography, (1975) Wiley.

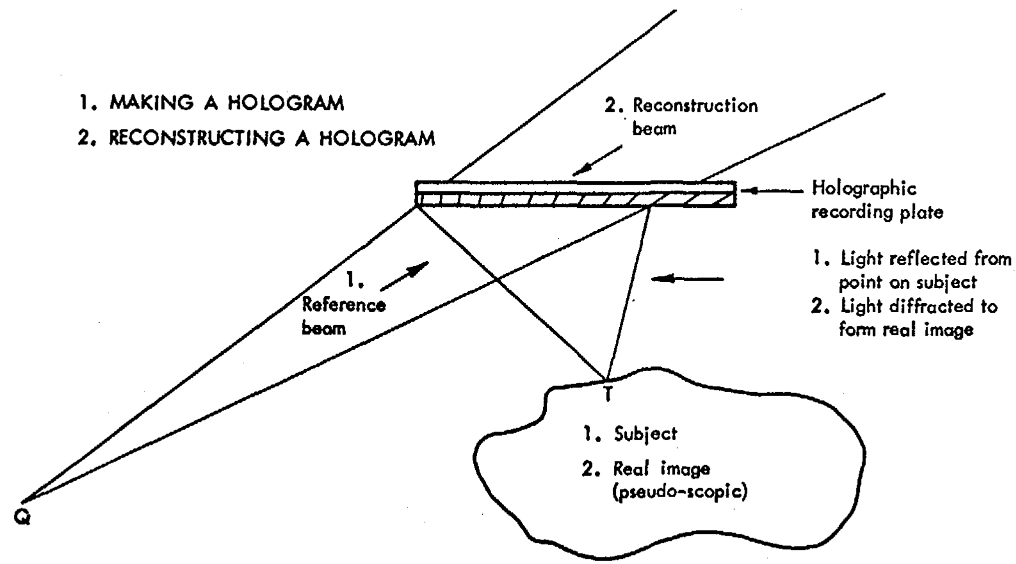
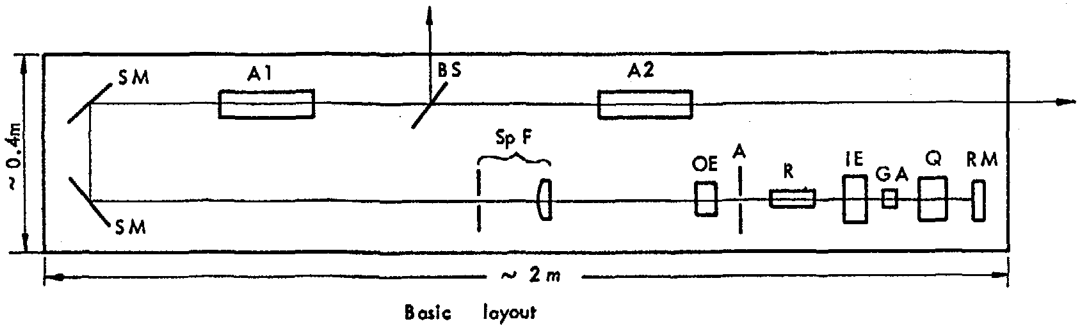


FIGURE 1. RECORDING AND RECONSTRUCTING A REAL IMAGE



Key:			
RM	Rear mirror	OE	Output etalon
Q	Pockel cell	Sp F	Spatial filter
GA	Glan air polarizer	SM	Surface mirror
IE	Intracavity etalon	A1	Amplifier 1
R	Ruby	A2	Amplifier 2
A	Aperture	BS	Beam splitter

FIGURE 2.

'Q' SWITCHED RUBY PULSED HOLOGRAPHIC LASER

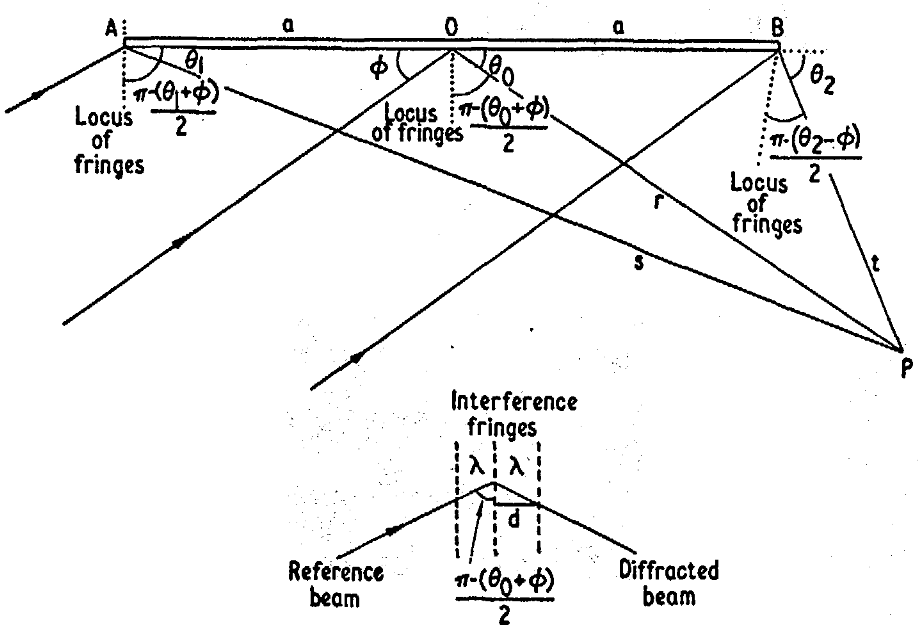


FIGURE 3

"Chromatic" aberrations in a hologram

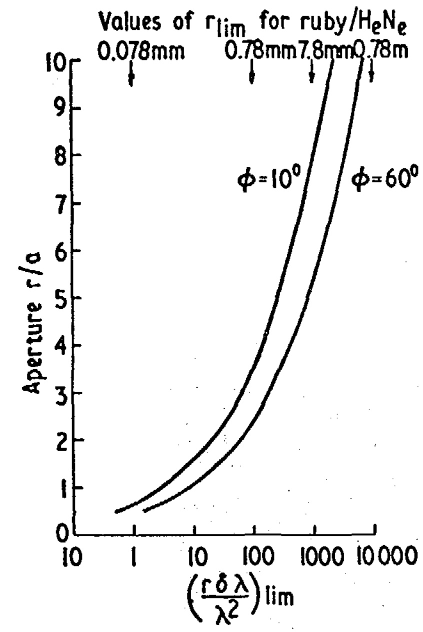


FIGURE 4

"Chromatic aberration" in transmission holograms for points $\theta = 90^o$ as ϕ_o

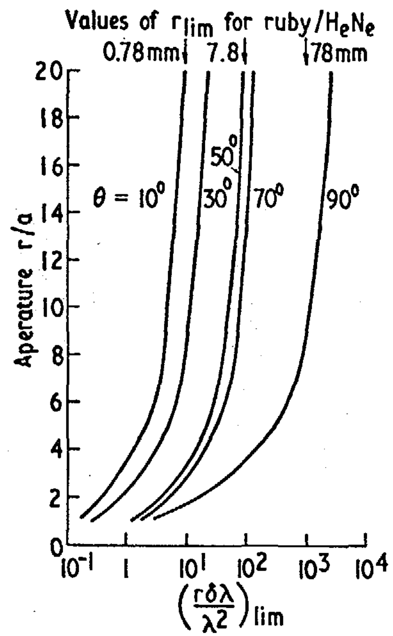


FIGURE 5.

"Chromatic aberration" in transmission holograms as a function of θ_o, ϕ_o = Constant = 10^o

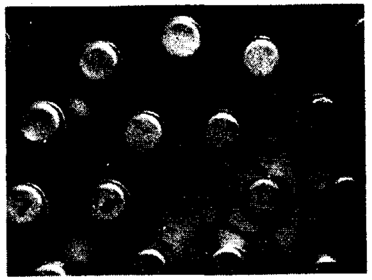


Figure 6(a)
End Caps

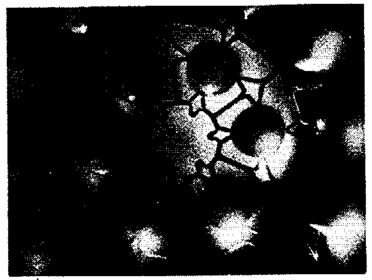


Figure 6(b)
Front Brace

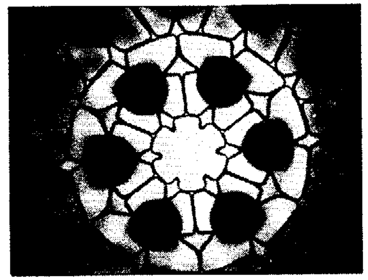


Figure 6(c)
Middle Brace

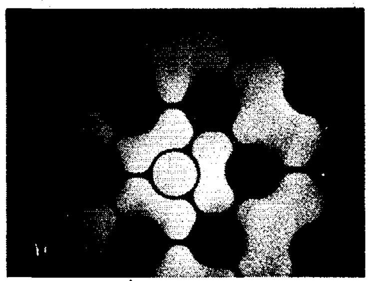


Figure 6(d)
Rear Grid

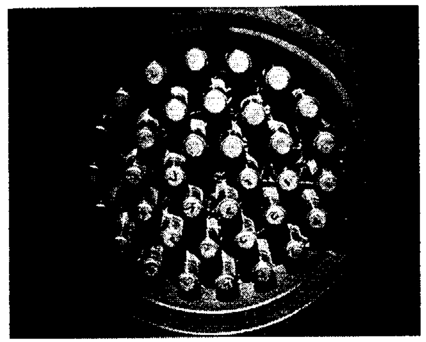


Figure 6(e)
Virtual Image

Figure 6: Series of holographically produced images taken along the axis of an AGR Fuel Element obtained from the 'real' image and (e) from virtual image

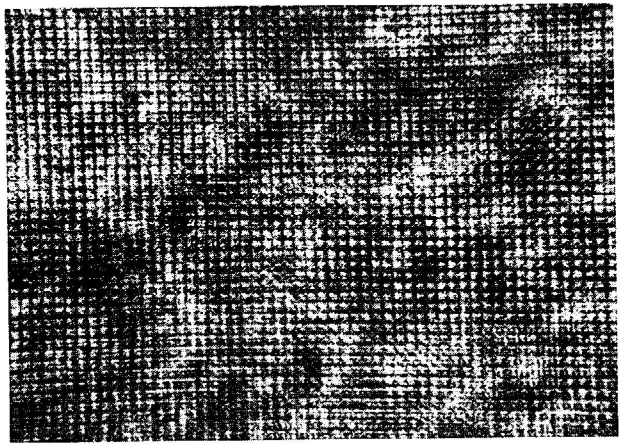


Figure 7
Photomicrograph of 40 μm mesh grid taken from holographically reconstructed real image.

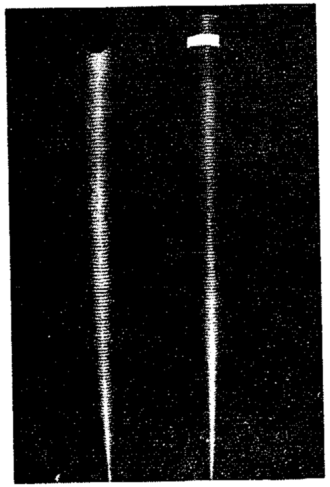


Figure 8(a)
Photograph obtained from virtual image of hologram of fuel pins subjected to artificial pressure testing.

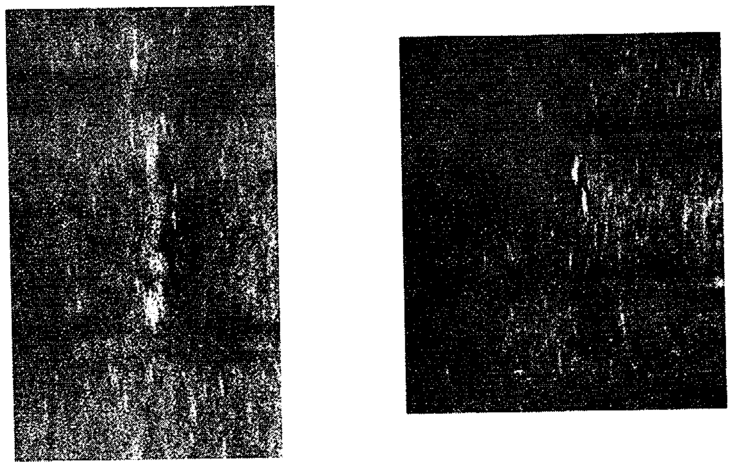


Figure 8(b)
Photomicrograph examination of holographic real image illustrating cracks.