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Catalysis Today 89 (2004) 337–341
CATALYSIS TODAY
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Real time opto-digital holographic microscopy (RTODHM)

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Abstract

The high development of numerical image and signal processing techniques, may lead to the replacement of conventional photosensitive media used in holography by CCD sensors: hence, to the field of digital holography. The hologram is saved in the host memory of a computer and can be reconstructed on the same place or elsewhere in a numerical manner. The development of liquid crystal displays (LCD) directly addressed by computer permits to think of opto-digital holography. The observation of the reconstructed image at a limited distance is possible when using adequate optical components, which makes not only the possibility to observe the image at a defined distance but also to control its magnification (opto-digital holographic microscopy). Since it is possible to control all experimental steps by adequate software, it is then possible to make real time opto-digital holographic microscopy. In this work, we show the experimental set-up and the obtained results, showing that this technique can be used to study different kinds of materials, connected to different conventional microscopes and to make holographic interferometry.

Keywords: Holography; Digital holography; Holographic microscopy

1. Introduction

Holography [1,2] is a technique of recording and reconstructing complete optical objects information, in amplitude and phase. This implies the necessity of means for recording and saving this information. If the recording mean is automatically the laser light because of its good coherence, the saving medium widely used is photosensitive materials (mainly those made from silver halide crystals). This kind of media is chosen for its high resolution (more than 2000 lines/mm) comparatively to ordinary photographic films (500 lines/mm). The main disadvantages of these media are their necessary chemical processing on one hand and the fact that the information is not quickly ready to handle with numerical techniques. To avoid these disadvantages and in order to make this technique automatic, several authors tried to use CCD sensors as recording media (digital holography).

Schnars and Jüptner [3] show the possibility to record the hologram with a CCD camera and to reconstruct the image in a numerical manner. The main problem is the resolution of the CCD detectors (nearly 100 lines/mm), which is less than that of ordinary films. That is the reason why the maximum angle between reference and object beams must be in the range of several degrees. Then, only small objects placed at large distances can be recorded. It is then a suitable technique for microscopical objects. However, the advantage is the possibility of image reconstruction at any time and space and making any transformation or calculation such as phase distribution determination [4] or making interferograms [4,5] numerically.

To overcome the CCD resolution problem, several set-ups were proposed and discussed. Xu et al. [6] gave a detailed explanation on recording conditions of a digital hologram. They studied the two principal configurations: in line and off axis holography. For numerical reconstruction, it is necessary to know how the amplitude distribution must be calculated and how the reference wave must be simulated. Fresnel and Fourier configurations are usually used; both are different just by the manner in which the reference wave is produced [7].

In many applications it is more suitable to make reconstruction optically such as experimental phenomenon observation, show educational works, etc.In the last few years, two kinds of displays have been developed; liquid crystal

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doi:10.1016/j.cattod.2003.12.017

displays (LCD) [8] and digital mirror displays (DMD) [9], which are directly addressed and controlled by computer. These elements make possible the optical reconstruction of digital holograms addressed on them, by transmission in the case of LCD and by reflection in the case of DMD.

The main problem of these elements is their pixel resolution, which is relatively low comparatively to holographic photoplates. This makes the reconstructing distance relatively big (several meters). To minimize this distance, it is necessary to introduce suitable optical components, so that, it is also possible to control the image magnification. It is then possible to make real time opto-digital holographic microscopy (RTODHM). In this paper, we present the backgrounds of opto-digital holography, the experimental set-up for RTODHM and the obtained results.

2. Theoretical backgrounds of DH

Holography [1,2] is known as a two steps optical technique for recording and reconstructing three-dimensional shapes. In the first step, one records on a photosensitive medium, the intensity distribution of the resulting interference phenomenon between the object and reference beams which is expressed by:

$$I = I_{\text{obj}} + I_{\text{ref}} + 2\sqrt{I_{\text{obj}} I_{\text{ref}}} \cos(\varphi_{\text{obj}} - \varphi_{\text{ref}}), \qquad (1)$$

showing that the illumination is modulated by a cosine term, giving rise to bright and dark fringes. This light distribution acts on the silver halide crystals spread on a glass plate making a diffraction grating with a spatial path (Λ) depending on the angle between the object and reference beams and the wave length of the used light (Fig. 1) which is given by:

$$\Lambda = \frac{\lambda}{\sin\theta} \qquad (2)$$

If one takes an angle between the two beams as 30° and works with a 632.8 nm laser light, then the spatial path

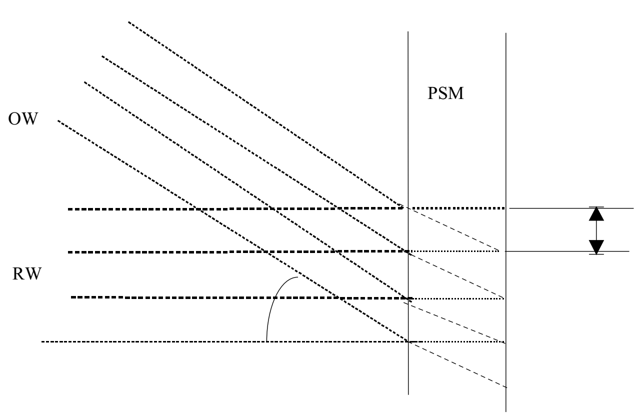

Fig. 1. Spatial representation of interfering fringes and angle between reference and object beams. RW: reference wave, OW: object wave, PSM: photosensitive medium, θ: angle between reference and object waves, Λ: fringe spacing path.

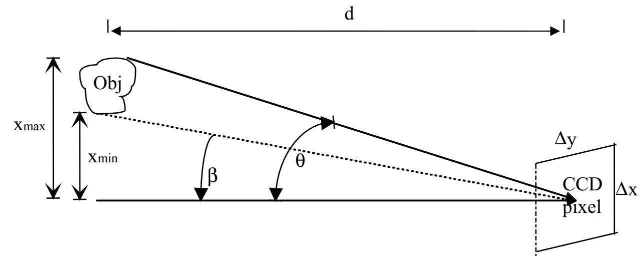

Fig. 2. Optimum position of the object. d: object CCD distance, $x_{\max}$: extreme object point, $x_{\min}$: maximum object shift, Δx, Δy: pixel size.

should be about 2.4 μm. The silver halide crystal diameter must then be in the range of 2 μm in order to resolve these fringes.

This is largely possible with this kind of photosensive media. Unfortunately, they have several problems, such as the necessity of the photoplate removing for its chemical processing, which takes a lot of time and introduces several aberrations on one hand and the difficulty to replace the photoplate at its exact place on the other hand. All these problems have made the holography a difficult and a relatively slow technique. The solution is then to record directly with CCD sensors [3,4]. The main problem however is the resolution of CCD sensors which is in the range of $(\Delta x) \times (\Delta y) = 8 \times 8\,\mu\text{m}^2$ by pixel. As minimum, it is necessary to take 2 pixels to detect a fringe, then, following Eq. (2), the maximum angle between the object and reference beams must be: $\theta = \arcsin(\lambda/2\,\Delta X) \approx 2^\circ$.

For digital holography of diffusing objects for which, besides of the maximum angle between the object and reference beams (θ), it is necessary to take into account the minimum shifting angle (β) of the object from the optical axis (Fig. 2), as given by [6]:

$$\beta_{\min} = \frac{3L_x}{2d} \qquad (3)$$

where L_x is the object lateral dimension in the direction x, placed at a distance (d) from the CCD sensors (Fig. 2).

On the information processing side, it is more suitable to use CCD sensors since the hologram can be handled more easily. It is possible to reconstruct the image at the same time and place or transfer it via a network elsewhere.

Thus, the amplitude and phase distribution in the real image plane (Fig. 3) can be found mathematically by the Fresnel–Kirchhoff integral [2]:

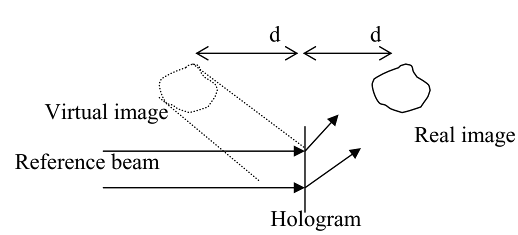

Fig. 3. Scheme of the holographic image reconstruction principle.

$$\Gamma(\xi,\eta) = \frac{ia}{\lambda d}\exp\left[-i\frac{\pi}{\lambda d}(\xi^2+\eta^2)\right] \times \iint t(x,y)\exp\left[-i\frac{\pi}{\lambda d}(x^2+y^2)\right] \times \exp\left[-i\frac{\pi}{\lambda d}(x\xi+y\eta)\right]\,\mathrm{d}x\,\mathrm{d}y \qquad (4)$$

where (a) is the incident wave amplitude, $t(x, y)$ is the amplitude transmittance of the hologram positioned at the plane ($z = 0$), (x, y) and (ξ, η) are the coordinates in the respective planes of the object and CCD detector and (d) is the recording and reconstructing distance (Fig. 3).

According to Schnars and Jüptner [3], the function given by Eq. (4) can be digitized if the hologram transmittance $t(x, y)$ is sampled on a rectangular field of ($N \times N$) matrix points with increments Δx, Δy along the coordinates. ξ and η are then replaced by ($r\,\Delta\xi$) and ($s\,\Delta\eta$) where (r) and (s) are real. In this case the discrete representation of Eq. (4) is given by [3]:

$$\Gamma(r,s) = \exp\left[-i\frac{\pi}{\lambda d}(r^2\Delta\xi^2+s^2\Delta\eta^2)\right] \times \sum_{k=0}^{N-1}\sum_{i=0}^{N-1} t(k,l)\exp\left[-i\frac{\pi}{\lambda d}(k^2\Delta x^2+l^2\Delta y^2)\right] \times \exp\left[i2\pi\left(\frac{kr}{N}+\frac{ls}{N}\right)\right] \qquad (5)$$

$\Gamma(r, s)$ is a matrix of ($N \times N$) points which describes the amplitude and phase distributions of the real image. From a numerical view, Eq. (5) is a representation of the Fresnel–Kirchhoff approximation in discrete Fourier transformation form. So, the reconstruction can be done numerically using the fast Fourier transform in every place and time, since the reference beam is in general simulated as a plane wave (Fig. 3).

With the development of the LCD [8] and the DMD [9], directly addressed by computer, it could be possible to reconstruct the image optically.

3. Experimental work and results

3.1. Opto-digital holography using LC2002

In order to develop the optical reconstruction, we built a set-up (Fig. 4) which makes possible the recording of digital holograms and their reconstruction via a LC2002 of (800 pixels × 600 pixels) and of 32 μm × 32 μm pixel size.

A green laser light beam ($\lambda = 532$ nm) of (73 mW) falls on a first beam splitter (S_1) of 70%/30% in order to give maximum energy to the reconstructing beam. The reflected beam which constitutes the reconstructing beam is enlarged and collimated. The polarizer and analyzer permit the visualization of addressed image on the display.

A second beam splitter (S_2) gives by reflection the object beam enlarged with a lens. Finally, a beam splitter cube gives also by reflection the reference beam. The attenuator serves to minimize the light intensity of the reference beam to avoid the camera saturation. A KAPPA CF 8/1 CCD camera, with a photosensitive surface of (6.4 H × 4.8 V) mm^2, constituted of (752 H × 582 V) pixels with (8.6 H × 8.3 V) μm^2 size and a rate frequency of 15,625 Hz is used to record the hologram.

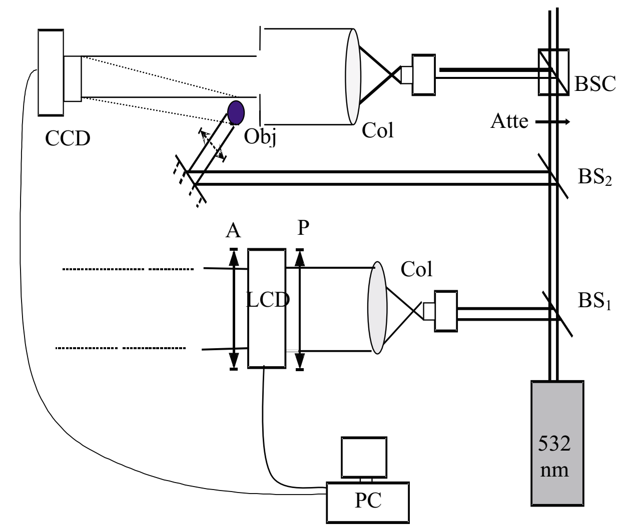

Fig. 4. Scheme of the opto-digital holographic experimental set-up. BS_1, BS_2: beam splitter, BSC: beam splitter cube, Atte: attenuator, Col: collimator, Obj: object, P: polarizer, A: analyzer, PC: personal computer, LCD: liquid crystal display.

After a preprocessing operation, the hologram is addressed on the LCD. The addressed hologram which is in reality a fringe field acts as a grating and diffracts the light passing through the LCD, giving the reconstructed image. The diffracted image is observed at a distance given by [9]:

$$d' = d\frac{\Delta x_{\mathrm{LCD}}}{\Delta x_{\mathrm{CCD}}}, \qquad (6)$$

where (d') denotes the reconstruction distance for optical reconstruction, (d) the recording one and (Δx_{LCD}, Δx_{CCD}) are the respective sizes of the LCD and CCD pixels in the (x) direction.

For LC2002 and a recording distance of 83 cm, the reconstruction distance is about 346 cm. Such a distance is relatively big and the diffracted orders are not perfectly distinguishable (Fig. 5). In order to minimize this distance and eliminate the superior orders, insertion of supplement optical components is necessary.

3.2. Real time opto-digital holographic microscopy (RTODHM)

It is possible to insert a first lens (L1) with a short focal length to focalize the diffracting figure from the display in order to separate diffraction orders. A diaphragm (D) permits to select only one image of diffraction figure of the display and a second lens (L2) permits to enlarge this image for observation (Fig. 6).

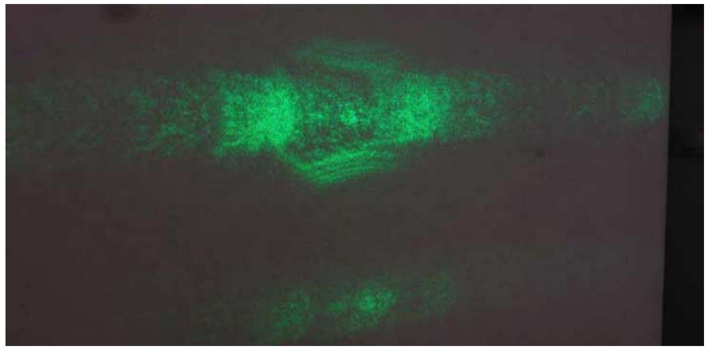

Fig. 5. Optical reconstructed image of a simple mirror as object.

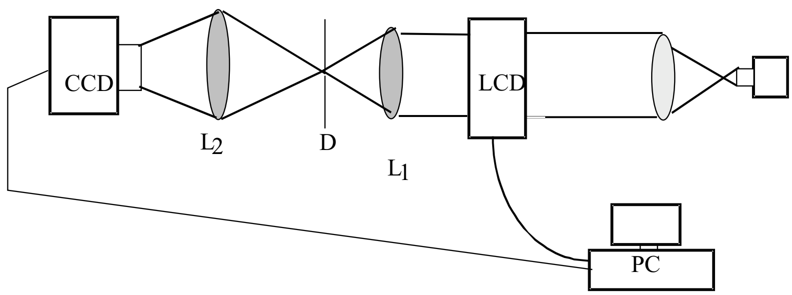

Fig. 6. Opto-digital holographic microscopy image reconstruction set-up. L1, L2: lenses, D: diaphragm.

The combination of these two lenses can be chosen according to their image quality or magnification degree. It is then possible to work in microscopy. Since it is possible to make software to automate all the process of acquiring, preprocessing and visualization, it is then possible to make RTODHM. It is also possible to make interferometric works [4] to study evolutions in dynamic objects.

Fig. 7 shows the reconstructed image of a section of 1 cm^2 of a steel plate and the Fig. 8 shows several parts of microscopical ceramic objects.

3.3. Discussion

As it can be seen, the obtained images have different significations and qualities. The first one (Fig. 5) shows the optically reconstructed image of a section of a mirror. It is not clearly distinguishable and has low contrast. It is obtained without supplement optical components so that, diffracting orders are closer together, which makes the image blurred. The second one (Fig. 7), shows also the optically reconstructed image of a section of 1 cm^2 of a steel plate, but with addition of supplement optical components for minimizing the reconstruction distance. Only the two first-orders are visible, giving each one a clear image, with good contrast and with an adequate magnification. The third one (Fig. 8), shows the optically reconstructed image of microscopical ceramic elements, also, at a reduced distance, for which the separation and magnification are adequate (several elements are distinguishable) but the contrast is very poor because of the speckle phenomenon [10] due to the coherent light and material nature.

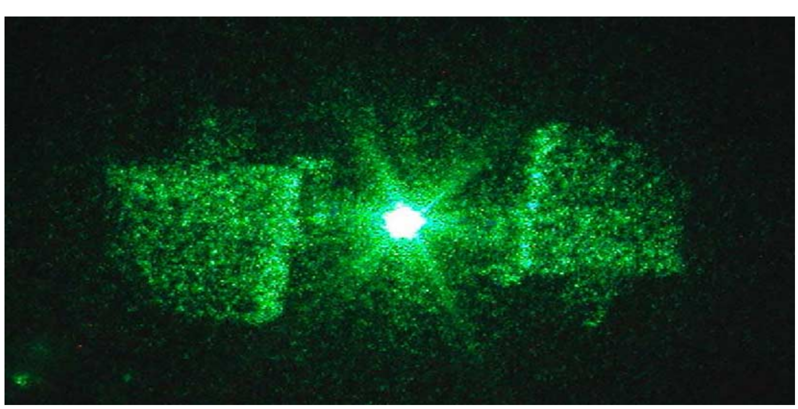

Fig. 7. Opto-digital holographic microscopy image reconstruction of a steel plate part.

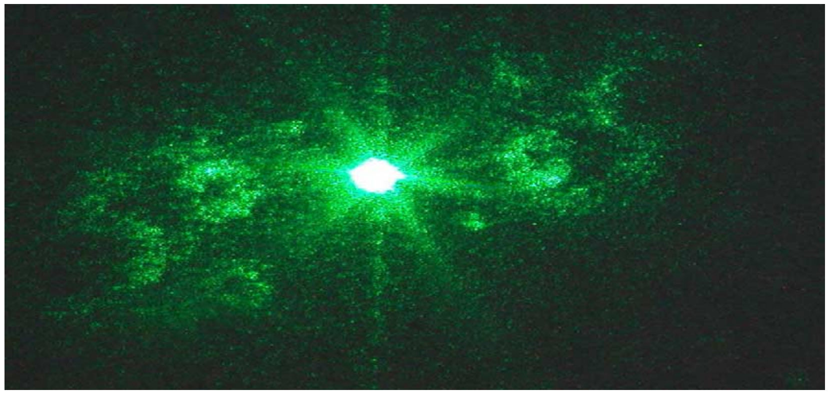

Fig. 8. Opto-digital holographic microscopy image reconstruction image of microscopical ceramic elements.

4. Conclusion

As it has been pointed out in this work, digital holography is more suitable for microscopical objects, especially those with good surface qualities. Since in microscopy works it is more suitable to observe the variation of the phenomenon in real time, it is then more adequate to use optical reconstruction. With this technique it is possible to control the image magnification optically by chosing the adequate optical components combination and to study numerically a particular detail.

This technique permits also to follow object modifications in real time by holographic interferometry, like strains and stresses. It is also possible to investigate work results on the same place or to transfer them via a network to different places.

Acknowledgements

We appreciate the continuous financial supports of the Deutscher Akademischer Austausch Dienst (DAAD).

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