Very high speed cw digital holographic interferometry

Carlos Pérez-López, Manuel H. De la Torre-Ibarra and Fernando Mendoza Santoyo

Centro de Investigaciones en Óptica A.C. Loma del Bosque 115 Lomas del Campestre, León, Guanajuato, México 37150

fmendoza@cio.mx

Abstract: It is reported for the first time the use of a very high speed camera in digital holographic interferometry with an out of plane sensitivity setup. The image plane holograms of a spherical latex balloon illuminated by a cw laser were acquired at a rate of 4000 frames per second, representing a time spacing between holograms of 250 microseconds, for 512 × 512 pixels at 8 bits resolution. Two types of tests were accomplished for a proof of principle of the technique, one with no constrains on the object which meant random movements due to non controlled environmental air currents, and the other with specific controlled conditions on the object. Results presented correspond to a random sample of sequential digital holograms, chosen from a 1 second exposure, individually Fourier processed in order to perform the usual comparison by subtraction between consecutive pairs thus obtaining the phase map of the object out of plane displacement, shown as a movie.

OCIS codes: (120.0120) Instrumentation, measurement, and metrology; (120.5050) Phase measurement; (120.4290) Nondestructive testing

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1. Introduction

Recent electronic devices like image cameras and computers for optical processing allow the use of different optical arrays to investigate fast transient phenomena. Optical experiments with conventional CCD cameras at low speeds using pulsed lasers have been reported, viz. [1, 2, 3]. High speed digital cameras have been used recently in speckle pattern interferometry to study resonant modes and transient events [4, 5, 6], where the optical phase can be obtained using additional hardware when the phase stepping method is used. It is already well known that the object phase may be retrieved without the use of any additional hardware by using digital holographic interferometry (DHI) [7, 8], whose optical set up is similar to that of ESPI [9]. Efforts towards gaining knowledge from very fast transient events, events that are not repeatable and indeed events that are difficult to control even in laboratory conditions, for instance biological samples, require the use of higher speed cameras with enough resolution or high repetition lasers with long coherence lengths, or a combination of both. It is for the first time reported here the use of a very high speed CMOS camera in digital holographic interferometry. Results were obtained for a 4000 frames per second rate at a pixel resolution of 512 × 512 with a constant pixel size of 16 μm and 8 bits of dynamic range. At this speed the image plane holograms were captured with a 250 μsec time separation, and individually processed in the usual manner, i.e., each digital hologram is Fourier transformed [10] in order to obtain the optical phase to finally, and even though the CMOS low resolution [11] and speed used in the experiments, compare by subtraction the optical phase from the digital holograms.

2. Method

An out of plane sensitive digital holographic interferometer is used. This interferometer setup is able to capture high speed images coming with a frame rate of 4000 images per second. Since a cw laser was used the intensity recorded by the camera sensor for every pixel (x, y) during an exposure time (τ) caused by the interference between the object and the reference beams can be expressed as,

$$\begin{aligned} I_1(x,y) &= \frac{1}{\tau}\int_0^{\tau}\left[a_1(x,y)+b_1(x,y)\cos(\psi+\phi_1+\phi_c)\right]dt \\ &\approx a_1(x,y)+b_1(x,y)\cos(\psi+\phi_1+\phi_c) \end{aligned} \tag{1}$$

For the case presented in this paper, it is assumed that during the camera exposure time the object motion change from frame to frame is slow enough to such an extent as to disregard without considerable errors the integration time and thus the average performed. For a dynamic event like a harmonic oscillation, the frequency at which the object vibrates has to be smaller compared to the camera exposure time for the integration time to be considered negligible. Otherwise, Bessel type fringes will be observed. The first term of the equation is the dc term present in the fringe pattern and the second term is the modulated interference term, where ψ is the random speckle phase, ϕ_l is the phase change coming from the object's deformation and ϕ_c is the angular shift introduced in digital holographic setups in the reference beam, otherwise described as a carrier frequency, a feature that may be observed in the Fourier domain. For a collection of n holograms, the intensity can be expressed in general form as,

$$I_n(x,y) = a_n(x,y)+b_n(x,y)\cos(\psi+\phi_n+\phi_c) \tag{2}$$

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where the first term $a_n(x, y)$ is the dc intensity between the reference beam an the n-th object beam. The second term of the equation is the modulation present in the n-th hologram. Equation (2) can be rewritten in exponential form as follows.

$$I_n(x,y) = a_n(x,y) + \left(\tfrac{1}{2}\right) b_n(x,y) e^{i(\psi+\phi_n+\phi_c)} + \left(\tfrac{1}{2}\right) b_n^*(x,y) e^{-i(\psi+\phi_n+\phi_c)} \qquad (3)$$

After Fourier transforming the last equation a modulation term due to ϕ_c, belonging to the second term and its conjugate, appears on the Fourier space symmetrically separated from the dc term. Applying a filter to eliminate one of the symmetrical and the low frequency $a_n(x, y)$ terms it is possible to obtain the relative phase difference after the inverse Fourier transform is applied. The n-th relative phase difference can be expressed as,

$$\Delta\phi_n(x,y) = \arctan \frac{\mathrm{Im}\left|\left(\tfrac{1}{2}\right) b_n(x,y) e^{(i\psi)} e^{(i\phi_n)}\right|}{\mathrm{Re}\left|\left(\tfrac{1}{2}\right) b_n(x,y) e^{(i\psi)} e^{(i\phi_n)}\right|} \qquad (4)$$

Equation (4) implies that it is possible to choose and set a reference state for the n-th holograms, e.g.,

$$\Delta\phi_{(n,r)}(x,y) = \phi_n - \phi_r \qquad (5)$$

$$\Delta\phi_{(n,n-1)}(x,y) = \phi_n - \phi_{n-1} \qquad (6)$$

This is possible if the deformation of the object remains within $-\pi < \Delta\phi_n < \pi$ for all the holograms, something that is possible to achieve due to the high frame rate used to capture this images. It is also important in order to apply a temporal unwrapping technique that shows the complete time of object dynamical object deformation or at any two consecutive images [12, 13, 5].

3. Experimental set up

Two experiments with a latex balloon were performed as a proof of principle of the technique with very high speed acquisition time. In the first experiment the object is freely moving by acting air currents in environment. The second experiment involves specific controlled conditions on the object that will be documented later in the text. Figure 1 shows the out of plane optical setup for very high speed digital holographic interferometry and used for both experiments, where the light source is a cw 6 watts maximum output power laser (Coherent Verdi V6) with a wavelength of 532 nm. Laser cw emission allows the object to be observed with the high speed camera (Nac fx6000) operating at 4000 frames per second, at 512 × 512 pixels resolution and 8 bits dynamic range (24 bit/pixel for any image format, RGB 8 bit each).

The capture time of the system is 250 microseconds with the electronic camera shutter open for all experiments. The laser beam is divided in object and reference beams. The object beam is expanded using a 10x microscope objective with spatial filter. The reference beam power is reduced and introduced into a single mode optical fiber that conveys the reference beam to the CMOS sensor where it is combined with the back scattered light coming from the object. The imaging lens has a focal length of 75 mm capturing the whole object on the CMOS sensor.

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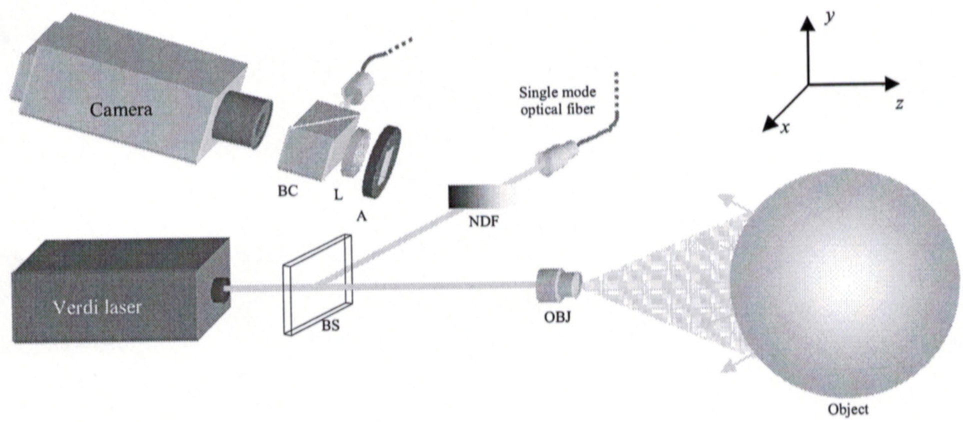

Fig. 1 Optical set up for DHI. (BS) is a 70/30 beam splitter, (BC) is a 50/50 beam combiner, (NDF) neutral density filter, (L) lens, (A) aperture and (OBJ) is a 10X microscope objective. The object under study is a 550mm diameter latex balloon.

During the experiments the object is placed in contact with a solid structure attached to a rigid table in order to avoid balloon rigid body motion. The object distance from the interferometer is long enough to manipulate the high power laser safely and have a small angle between the illumination and the observation direction. The last condition assures that the system is sensitive to, mainly, out of plane displacements. It should be pointed out here that the shape of the object was neither experimentally nor theoretically calculated to be used in conjunction with the out of plane data deformation obtained. It is considered that this information is not needed at this stage of the research. Furthermore, the object to lens distance is such that the round contour of the balloon may be taken as a flat in the image plane within a fairly good approximation.

3.1 Free motion

The first experiment consists in taking the digital holograms from the object with no constrains, i.e., once inflated to an unspecified air pressure leave it to take random air currents present in its surroundings, so the object is suffering fast deformations over its surface. 815 images were recorded in an event lasting 203.75 ms, a good enough time period for the study of transient events. For the quoted frame rate the laser output power was set at 5.5 W, enough to have light scattered coming from the untreated object surface into the CMOS sensor. Even when it is possible to observe interference fringes on the sample using an ESPI system, the phase extraction is complicated considering how fast image to image de-correlate. The camera has a relative high resolution of 512 × 512 pixels, however considering that the inspection area is large, 300mm × 300mm, the system will resolve mainly smooth changes of the object. The surface displacements were of the order of nanometers and that can be easily detected with this system.

The relative phase difference is calculated considering a reference state which means having 814 relative phase maps. A lineal filter of 3×3 is implemented in order to reduce the noise present in the digital holograms, as compared to previous efforts where a 7x7 convolution average filter was used [11]. Commercial 2D unwrapping software is used (PV_SPUA2, Phase Vision Ltd.) successfully. Figures 2(a) to 2(d) shows a high speed sequence of four instants of free motion where it is possible to observe the dynamic movement present in the object due to the air currents. The deformation is clearly visible, with qualitative and quantitative understanding gained from images such as these where the fringe pattern, and the wrapped and unwrapped phase maps are shown simultaneously.

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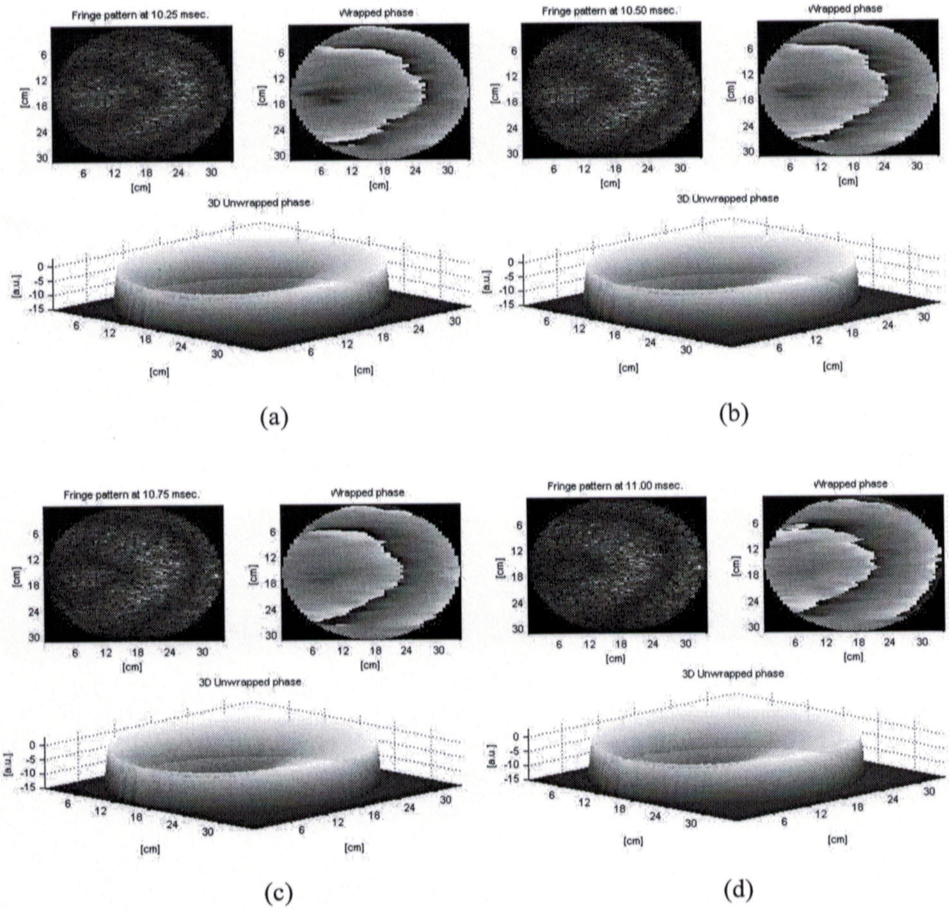

Fig. 2 Four different instants showing the free motion of the balloon. a) 10.25 ms b) 10.5 ms c) 10.75 ms d) 11.0 ms. The full series of holograms are shown in a movie like format.

3.2 Constrained motion

The same latex balloon is used, but special conditions are introduced as shown in figure 3, namely, three rubber panels are attached to the table in order to limit the balloon freedom of movement with the optical system remaining the same, figure 1. This test was designed in order to observe fringe changes considering that the latex surface is soft enough to suffer boundary conditions and act like a membrane. The balloon is inflated at 0.145 psi pressure which stays constant during the recording of data, in accordance to the assumption made in section 2. Once the balloon reaches the walls constraining it the gas within starts pushing the walls creating a bouncing wave that reflects its activity on the balloon surface. The same frame rate of the camera is used to obtain the holograms during a time period of 203.75 ms, and phase maps obtained considering one reference state for all of them. Figures 4(a) to 4(d) show four different instants of deformation of the balloon where it is possible to observe that in fact it has a remarkable difference in its behavior as compared to the free motion test. In this case the surface of the object responds like a membrane stimulated with an external frequency [14].

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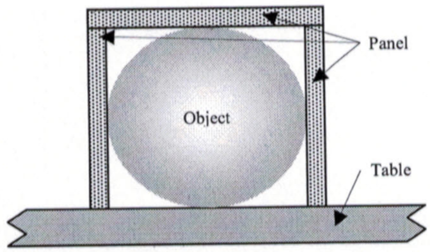
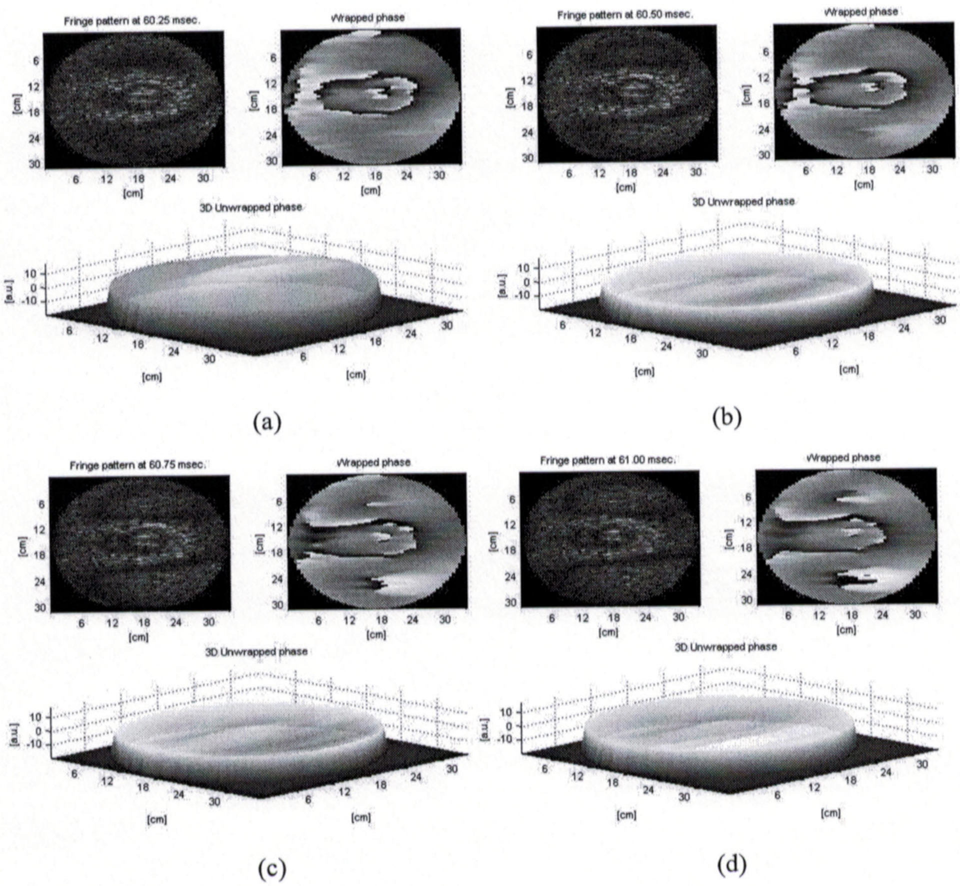


Fig. 3 Boundary conditions added to the object for the second test. Rubber panels keep the object static all around except the observe area.



(a) (b)

(c) (d)

Fig. 4 Four different instants showing the constrained movement of the balloon. a) 60.25 ms b) 60.5 ms c) 60.75 ms d) 61.0 ms. The full series of holograms are show in a movie like format.

4. Conclusions

The successful implementation for the first time of very high speed DHI was possible using a high power cw laser and a high speed CMOS camera, at an acquisition rate of 4000 frames per second with no extra data processing, as compared to conventional low speed DHI, in order to obtain relative good phase maps and their unwrapped data with high quality. This very high speed frame rate shows the displacement evolution during fast events. The object under study is easy to deform but represents a challenge during its inspection: latex surfaces present rapid changes difficult to study with a lower speed systems. Fast de-correlation effects were avoided with this technique for an object wide angle field of view of 300mm. Work will be done in the very near future in order to incorporate the object shape and to perform measurements in 3D.

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