# Digital holographic microscope with automatic focus tracking by detecting sample displacement in real time

**Pietro Ferraro and Giuseppe Coppola**

*Istituto per la Microelettronica e Microsistemi del Consigilio Nazionale delle Ricerche, Via P. Castellino 111 80134 Naples, Italy*

**Sergio De Nicola, Andrea Finizio, and Giovanni Pierattini**

*Istituto di Cibernetica "Eduardo Caianiello" del Consiglio Nazionale delle Ricerche, Via Campi Flegrei 34, 80078 Pozzuoli (Naples), Italy*

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We propose a new method for focus tracking during the recording of a sequence of digital holograms while the sample experiences axial displacement. Corrected reconstruction distances can be automatically calculated, and well-focused amplitude and phase-contrast images can be obtained for each digitized hologram. The method is demonstrated for inspection of microelectromechanical systems subjected to thermal load. The method can be applied as a quasi-real-time procedure. © 2003 Optical Society of America

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In digital holography (DH) the holgoram is recorded by a CCD while intensity and phase reconstruction are performed numerically.[1] In DH quantitative phase-contrast imaging[2–4] and aberration compensation are possible.[4–7] DH has been applied in fields such as deformation analysis, object contouring, measurement of particle position, and encryption.[1] DH has also been investigated for object recognition[8] and comparative analysis.[9] Phase shifting in DH has been studied for error reduction[10] and color display applications.[11] A significant improvement of spatial resolution has been demonstrated for DH with synthetic apertures.[12,13] DH is also useful for characterization of microelectromechanical systems (MEMS).[14–17] In DH the image plane for best focus can be determined by *a priori* knowledge of parameters such as the focal length of the microscope objective (MO), the distance between the object and the MO, and the distance between the plane of the hologram and the MO. In a real situation, however, it may be difficult to know or measure those parameters. Since DH has the advantage of numerical reconstruction, one can find the focus by performing numerical reconstructions at different distances in analogy with mechanical translation of the MO in conventional microscopy. This numerical method can be time consuming and impractical when a long sequence of holograms has been recorded with the image plane varying unpredictably. Since in DH microscopy an imaging short focal lens is required, if the sample experiences even very small displacements along the optical axis, a very large change occurs in the distance to the imaging plane, and the focus can be lost. In this case the distance used in the numerical reconstruction process has to be changed to get an in-focus amplitude or phase-contrast image. Displacement of the object may occur for different reasons. One unavoidable situation is encountered in thermal characterizaiton of samples. Naturally temperature changes cause thermal expansion of the sample and its mechanical support that may not be predictable. A small axial displacement, even in the micrometric range, shifts the image plane and changes the reconstruction distance. The tedious and cumbersome search for new focal planes becomes intolerable, especially if there is the need to visualize the phenomenon in anything approximating real time. We present a method for detecting the axial displacement of the sample in real time by measuring the phase shift of the hologram fringes. In this way we obtain the incremental change of the distance to be used in the numerical reconstruction. As a result, in-focus amplitude and phase-contrast images for each recorded hologram can be reconstructed. We demonstrate a quasi-real-time application of the method for inspection of silicon MEMS structures while the temperature is changed. The procedure is fully automatic and obtains reconstructed amplitude and phase-contrast images in best focus. Figure 1 shows the experimental setup. The laser has the wavelength $\lambda = 532$ nm. The MO is an aspheric lens with the focal length $f = 15.36$ mm and a numerical aperture of 0.16 equivalent to ten times the MO. The 6.7-$\mu$m square CCD has $1280 \times 1024$ pixels. The beam illuminating the object was collimated. In this configuration any axial displacement of the object caused a shift in the fringe pattern of the hologram. By recording the phase shift in a small flat portion of the object, it is possible to determine the displacement. If $p$ is the distance from the lens to the object, $q$ is the distance of the image plane from the lens, and $f$ is the focal length, then any axial displacement $\Delta p$ of

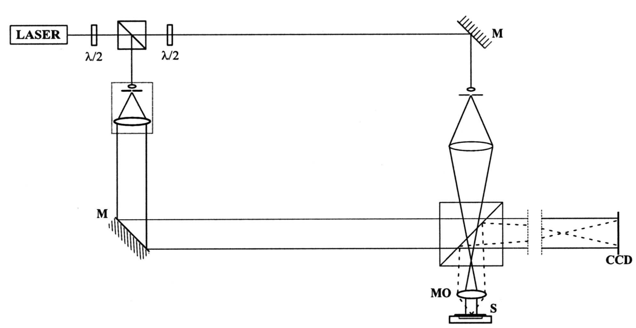


Fig. 1. Optical setup of the DH microscope. MO, microscope objective; M, mirror; S, sample.

 

the sample results in a translation of the imaging plane in front of the CCD given by

$$\Delta q = -M^2 \Delta p\,, \tag{1}$$

where $M = q/p$ is the magnification. The displacement $\Delta p$ is given by

$$\Delta p = \frac{\Delta\varphi(t)}{4\pi}\lambda\,, \tag{2}$$

where $\Delta\varphi(t)$ is the phase shift detected at time $t$. From Eq. (2) we see that a displacement of 10 $\mu$m translates the image plane by $\Delta p = 16$ mm if $M = 40$. We tested two silicon MEMS structures with out-of-plane deformation caused by the residual stress induced by the microfabrication process[17,18]—a cantilever (50 $\mu$m $\times$ 50 $\mu$m) and bridges 10 $\mu$m wide. The silicon wafer was mounted on a metal plate and held by a vacuum chuck system. The metal plate was mounted on a translation stage in proximity to the MO. The sample was heated in the range 23–120 °C by a remote-controlled heating element. Axial displacement was caused by the overall thermal expansion of the metallic plate and the translation stage. The first hologram was recorded before the temperature was raised. The numerical reconstruction for a well-focused image was found at an initial distance of 100 mm with an estimated magnification $M = 40$. While heating the sample, we detected the phase shift of the fringes in real time by measuring the average intensity change in a group of $4 \times 4$.

The inset in Fig. 2 shows the recorded intensity signal. The signal had 3149 points sampled at a rate of 12.5 points/s. At every tenth point a hologram was digitized. The signal in Fig. 2 was analyzed by applying a Fourier-transform method.[18] For each point recorded the wrapped phase was detected and the unwrapped phase was calculated. The displacement $\Delta p$ was calculated from Eq. (2) and is shown in Fig. 2 as a function of the sampled point. The numerical reconstruction distance for each hologram was continuously updated.

As shown in Fig. 2, the final hologram reconstruction distance differs from the initial distance by ~40 mm. Figures 3a, 3b, and 3c show the amplitude and phase-contrast reconstructions for the cantilever beam from three different holograms in the recorded sequence of 314 holograms; holograms 1, 196, and 314 correspond to three different teperatures. We performed the reconstructions automatically by applying the focus-tracking procedure. Figure 3a shows the reconstruction of hologram 1 at $d = 100$ mm. Fig. 3b shows that of hologram 196 at $d = 117.3$ mm, and Fig. 3c shows that of hologram 314 at $d = 140.8$ mm. The reconstructions were performed numerically by the Fresnel transformation method, and the dc term was eliminated by application of a high-pass filter to the hologram.[1] In the phase-contrast image the wrapped phase observed on the cantilever indicates that it had an intrinsic out-of-plane deformation. As expected, the reconstructions in Fig. 3 are all in focus. In Figs. 3b and 3c the size of the reconstructed object is smaller because of the larger reconstruction distance. Furthermore, all 314 holograms in the sequence were reconstructed in focus, which demonstrates the validity of the method. Figure 4 shows a different MEMS structure with a bridge shape and with smaller dimensions. Figure 4a shows the amplitude of the last recorded hologram (314) from another sequence at $d = 138$ mm from the focus-tracking procedure. For comparison Fig. 4b shows the reconstruction of the same hologram at $d = 100$ mm without taking the focus change into account. The effect of focus tracking in amplitude reconstruction is clear. Figures 5a, 5b, 5c, and 5d show the phase, wrapped and unwrapped, of the lower MEMS bridge from Fig. 4. Figure 5 shows that the effect of defocus also influences the phase-contrast reconstruction, thereby affecting the quantitative information. In particular it is clearly visible that the edges of the bridge are blurred when the focus-tracking method is not applied.

A new method for tracking focus during the recording of a sequence of holograms has been proposed. In this way a corrected reconstruction distance for each acquired hologram and well-focused amplitude and phase-contrast images can be obtained. The method can be applied as a quasi-real-time procedure. It could constitute a significant step forward in the implementation of a DH microscope for quasi-real-time observation in many fields of application. In principle,

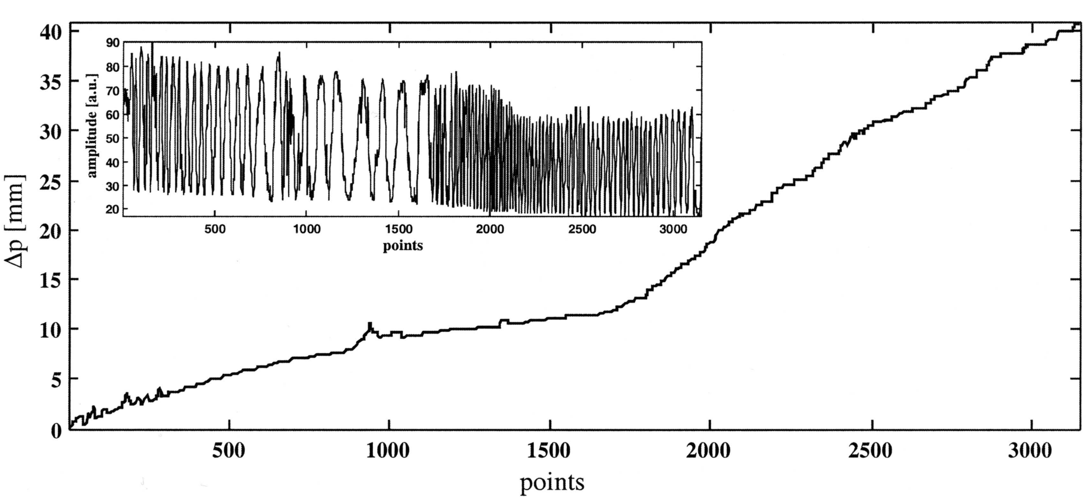


Fig. 2. Displacement of the sample measured in real time by analyzing the phase shift (inset) of hologram fringes.

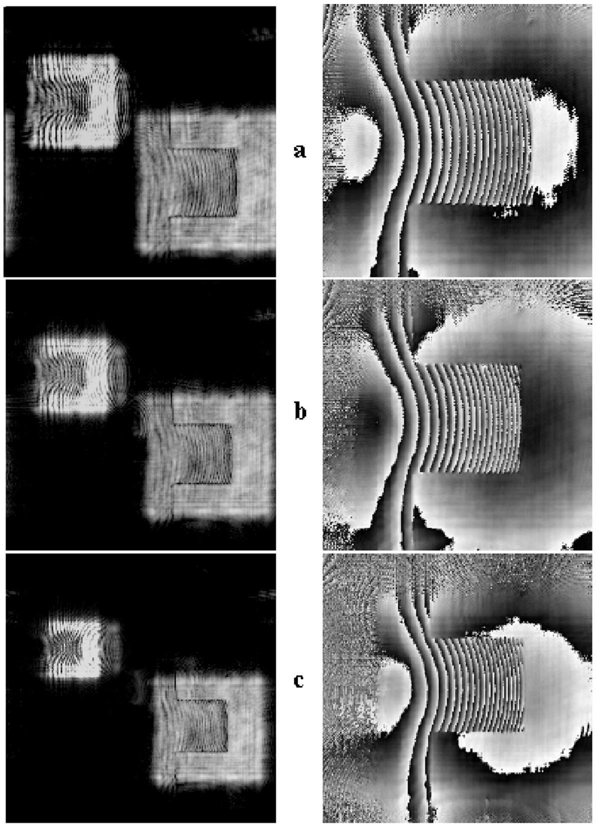


Fig. 3. In-focus amplitude and phase contrast for the cantilever beam from three holograms (a, 1; b, 196; c, 314) of the recorded sequence obtained by applying the focus-tracking procedure.

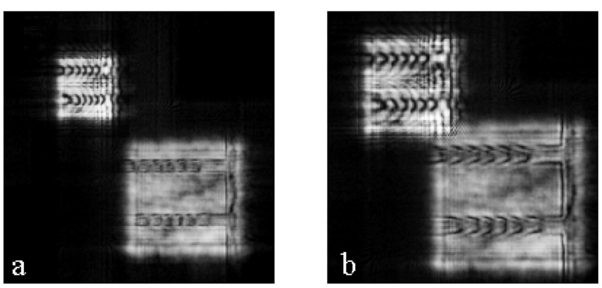


Fig. 4. In-focus amplitude reconstruction of a bridge, a, at $d = 138$ mm, by the focus-tracking procedure and, b, at $d = 100$ mm without taking into account the focus change.

if three phase shifts are measured at three points in the hologram, it would also be possible to track tilts, allowing focus tracking in tilted image planes.

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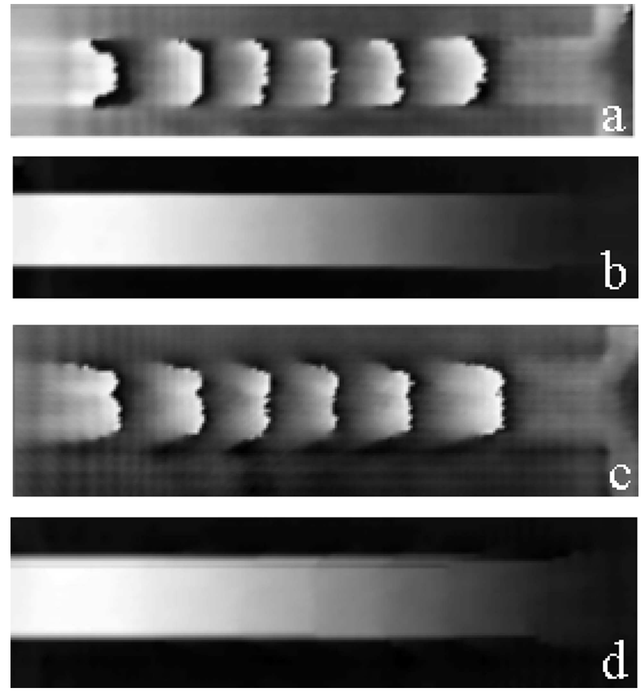


Fig. 5. Wrapped and unwrapped phase-contrast reconstruction, respectively, of the lower MEMS bridge from Fig. 4: a, b, applying the focus-tracking procdure; c, d, without focus-tracking.

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