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Digital Holography, a metrological tool for quantitative analysis: Trends and future applications

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A B S T R A C T

A review on the last achievements of Digital Holography is reported in this paper, showing that this powerful method can be a key metrological tool for the quantitative analysis and non-invasive inspection of a variety of materials, devices and processes. Nowadays, its range of applications has been greatly extended, including the study of live biological matter and biomedical applications. This paper overviews the main progresses and future perspectives of digital holography, showing new optical configurations and investigating the numerical issues to be tackled for the processing and display of quantitative data.

1. Introduction

In the recent years, Digital Holography (DH) has become a valuable tool for diagnostic and characterization in different fields of science and technology. The advancements are mainly due to the progresses of laser technology, digital detectors and computer processing techniques. The main advantage of DH, in respect to classical holography, is the direct access to the phase maps by the numerical solution of the diffraction problem, from which other attractive features of DH arise, like focus flexibility, 3D imaging properties, 3D object tracking, that is the ability to extract quantitative data by means of numerical processing of digital holograms [1–4]. Then, quantitative phase maps are processed for metrology purposes by defining and calculating suitable metrics with corresponding measurement uncertainties [3]. In this paper, we review the chief developments that have been reached in the last decade about DH techniques, showing some of the more relevant applications. In particular, we show how DH can be used as inspection tool for microelectromechanical systems (MEMS), for 3D characterization of micro-lenses optical properties, and, above all, as label-free quantitative analysis tool in life sciences.

2. DH as quantitative tool for MEMS inspection

Microelectromechanical systems (MEMS) are micro devices that integrate mechanical elements, electronics, sensors, and actuators in a small volume [5]. MEMS are realized using different material layers superimposed in various process steps, thanks to the microfabrication technology, starting from a common silicon substrate [6,7].

Production of silicon MEMS requires complex procedures, of the same type as those for integrated circuits (i.e. chemical or plasma etching, high temperature), that could induce damages or residual stresses and undesired in-plane and out-of-plane deformations that can compromise the final performances.

Moreover, the MEMS can deteriorate during the successive handling operations or because of the aging process, thus limiting performance in the actuation phase. For these reasons, the characterization of the mechanical properties at different fabrication steps or during operation mode can be very useful. In this context, DH has been utilized as tool for optical metrology measurements to characterize MEMS structures in a non-destructive way in static and dynamic condition [8–12].

2.1. Extending the depth of focus

An important issue in the evaluation of MEMS surfaces is related to the microscopy paradigm: the higher the required magnification, the lower the depth of focus. For a MEMS, that, in most cases, is an object with a 3-dimensional complex shape, only a part of the entire volume appears in good focus to the observer who is looking at a single image plane. DH overcomes the problems of typical mechanical scanning thanks to its most important feature, that is the focus flexibility and the quantitative phase imaging.

In fact, starting from a single digital hologram, through the reconstruction of numerical images at different image planes (i.e., at a different distance d [13]) it is possible to obtain an extended focus image with all surface details of MEMS in evidence, without changing the distance between the object and the microscope objective [14–16]. Thus, it is possible to get the entire volume by changing in the reconstruction algorithm the distance parameter d along the z axis, thus obtaining one single in focus image section.

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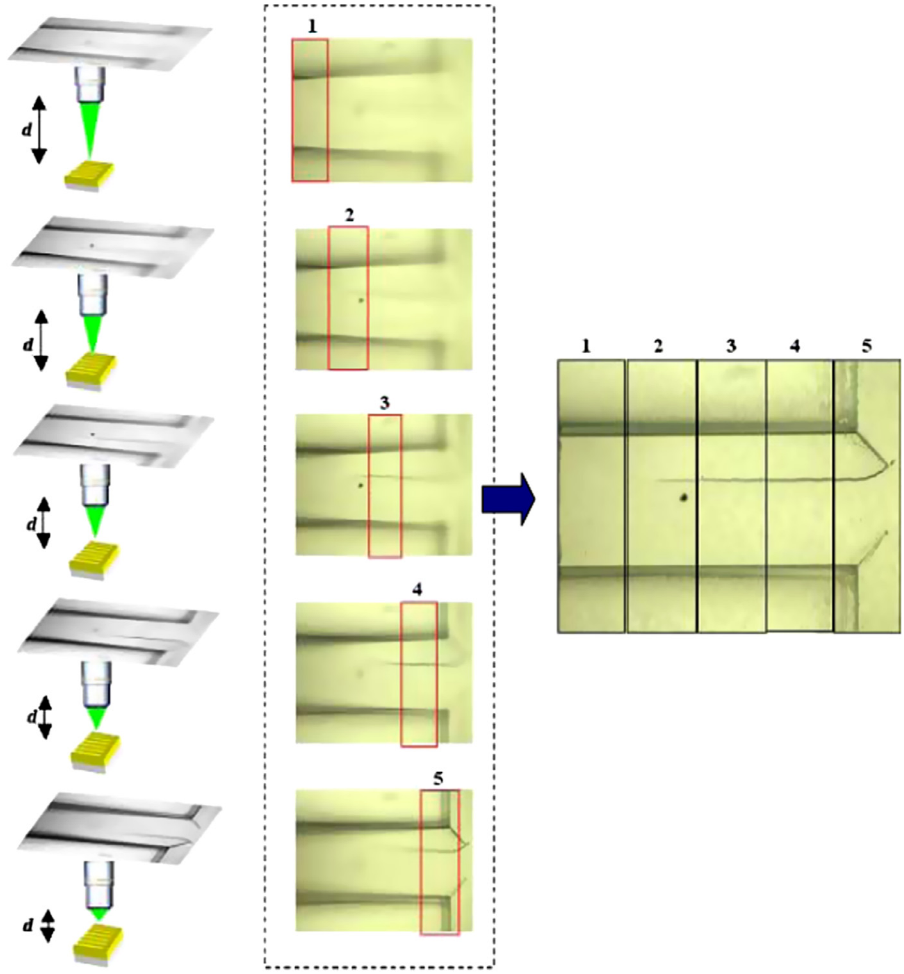

Fig. 1. Qualitative drawing of the working principle of the EFI method. Stack of in focus images corresponding to different portions of the imaged object are stuck together to get an overall in-focus image (on the right side). [13].

It must be stressed that in DH, according to the following expressions, the reconstruction pixel in the image plane increases as a function of the reconstruction distance:

$$\Delta\xi = \frac{d\lambda}{N\Delta x} \tag{1}$$

$$\Delta\eta = \frac{d\lambda}{M\Delta y} \tag{2}$$

where N × M is the matrix dimension of the reconstructed image, and Δx and Δy are the pixel pitches of the camera sensor. It is clear that to obtain an in-focus stack of images (see Fig. 1), it is necessary to control the size of the object independently from the reconstruction distance. Moreover, the reconstructed image is centered by modelling the reference beam appropriately [17–20].

The numerically reconstructed phase map $\varphi(x, y)$ in DH holds information about the MEMS profile; in fact the optical path difference is given by the relation:

$$OPD\ (x, y) = \varphi(x, y)\ \frac{\lambda}{2\pi} \tag{3}$$

If p represents the distance from the lens to the lowest point of the object, and q is the corresponding distance of the image of that point from the lens, then any other point of the object at different depth Δp(x,y), results in focus at a different imaging plane (in front of the camera sensor), according to the following relation:

$$\Delta q\ (x, y) = -M^2 \Delta p(x, y) \tag{4}$$

Where M = q/p is the magnification. Because the optical path difference is given by the relation:

$$OPD\ (x, y) = \varphi(x, y)\frac{\lambda}{2\pi} = 2\Delta p(x, y) \tag{5}$$

in a reflection configuration, the range of distances, at which the digital hologram has to be reconstructed to image all the volume in focus, results to be:

$$\Delta q\ (x, y) = -M^2 \Delta\varphi(x, y)\ \frac{\lambda}{4\pi} \tag{6}$$

Taking in account these considerations, the Fig. 2 shows the deformation of a silicon cantilever that is highly deformed due to the presence of a residual stress, induced during the fabrication process. In particular, Fig. 2d shows the resulting focused profile of the entire structure. Anyway, for a precise determination of 3-D displacement vectors of complex objects, the 3-D shape of the surface is required [21].

2.2. Time-averaged digital holography

Time average holography is an experimental method basically used for analyzing the surface oscillations [20,22] that has been employed in dynamic micro-metrology [23,24], dynamic characterization of MEMS diaphragm [25], and measurement of static and vibrating microsystems [26]. When a rough object is stressed with a pure sinusoidal excitation, the resulting optical phase variation can be written as $\Delta\varphi(t) = \Delta\varphi_0 + \Delta\varphi_m \sin(\omega_0 t + \varphi_0)$ where $\Delta\varphi_0$ is an offset term, $\Delta\varphi_m$ is the maximum amplitude of the vibration at pulsation ω_0, and φ_0 is the phase