Геометричні та координатно-часові вимірювання

UDC 537.533

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METHODS AND INSTRUMENTATION OF DIGITAL HOLOGRAPHY IN MICRO AND NANO METROLOGY

The need for dimensional micro and nano metrology is evident, and as critical dimensions are scaled down and geometrical complexity of objects is increased, the available technologies appear not sufficient. Major research and development efforts have to be undertaken in order to answer these challenges. The developments have to include new measuring principles and instrumentation, tolerancing rules and procedures as well as traceability and calibration. Digital holography is an emergent new imaging technology that inherits many of the unique capabilities of conventional holography but provides novel solutions to some of the key problems that have been limiting its applications and further development.

Key words: *nano metrology, digital holography, microscopy, interferometry, CCD-camera.*

Abstract

A conventional holographic interferogram is generated by superposition of two waves, which are scattered from an object in different states. The interferogram carries the information about the phase change between the waves in form of dark and bright fringes.

The interference phase is usually calculated from three or more phase shifted interferograms by phase shifting algorithm. This requires additional experimental effort.

Digital Holography allows a completely different way of processing. In each state of the object one digital hologram is recorded. Instead of superimposing these holograms as in conventional HI using photographic plates, the digital holograms are reconstructed separately

Since mid nineties of the last century Digital Holography has been extended, improved and applied to several measurement tasks. Important steps are:

- improvements of the experimental techniques and of the reconstruction algorithm;
- applications in deformation analysis and shape measurement the development of phase shifting digital holography;
- applications in imaging, particle tracking and microscopy;
- measurement of refractive index distributions within transparent media due to temperature or concentration variations;
- applications in encrypting of information;
- the development of digital light-in-flight holography and other short-coherence length applications;
- the combination of digital holography with heterodyne techniques;
- the development of methods to reconstruct the three-dimensional object structure from digital holograms;
- the development of comparative Digital Holography;
- the use of a Digital Mirror Device (DMD) for optical reconstruction of digital holograms (DMD).

The current paper describes issues in dimensional micro and nano metrology by reviewing available instrumentation methods.

1. Methods of Digital Holography Microscopy

The depth of field of imaging systems decreases with increasing magnification. In microscopy the depth of field is therefore very limited due to the high magnification.

Direct Method. The investigation of a three dimensional object with microscopic resolution requires therefore certain refocusing steps. Digital Holography offers the possibility to focus on different object layers by numerical methods. In addition, the images are free of aberrations due to imperfections of optical lenses.

In order to obtain a high lateral resolution in the reconstructed image the object has to be placed near to the CCD. The necessary distance to obtain a resolution $\Delta\varepsilon'$ with the Fresnel approximation can be estimated with Eq (1):

$$\Delta\varepsilon' = \frac{\lambda d'}{N\Delta x}, \qquad \Delta\eta' = \frac{\lambda d'}{N\Delta y}. \tag{1}$$

The apostrophe is introduced in order to decide between object distance d in the recording process and reconstruction distance d'. We will see that these distances are different for holographic microscopy. With a pixel size of Δx = 10µm, a wavelength of λ = 500 nm, 1000 x 1000 pixels and a required resolution of $\Delta\varepsilon'$=1µm a reconstruction distance of d' = 2 cm results. Typical pixel sizes for high resolution cameras are in the range of 10 µm x 10 µm, too low for microscopy. Therefore the reconstruction procedure has to be modified.

Magnification can be introduced by changing the wavelength or the position of the source point of the reference wave in the reconstruction process. In Digital Holography the magnification can be easily introduced by changing the reference wave source point.

A set-up for digital holographic microscopy is shown in figure 1.1. The object is illuminated in transmission and the spherical reference wave is coupled into the set-up via a semi-transparent mirror. Reference and object wave are guided via optical fibres. For weak scattering objects one can block the external reference wave and work with an in-line configuration. The resolution is about 2.2 µm.

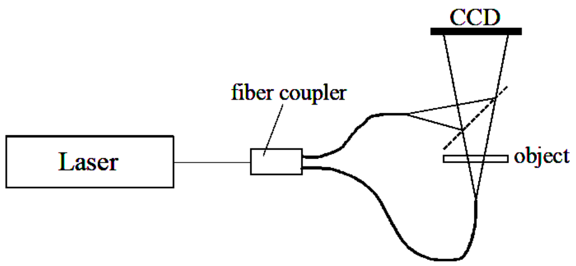

Fig. 1.1. Digital holographic microscope

Phase Shifting Digital Holography Method

Phase Shifting Digital Holography has been also applied to microscopy. The principle of this method is shown in the set-up of figure 1.2. A light beam is coupled into a Mach-Zehnder interferometer. The sample to be investigated (object) is mounted in one arm of the interferometer. It is imaged onto the CCD target by a microscope objective (MO). A second objective is mounted in the reference arm in order to form a reference wavefront with the same curvature.

Both partial waves interfere at the CCD target. An image of the sample superimposed by a coherent background (reference wave) is formed onto the CCD target. A set of phase shifted images is recorded. The phase shift is realized by a piezo electric transducer in the reference arm of the interferometer.

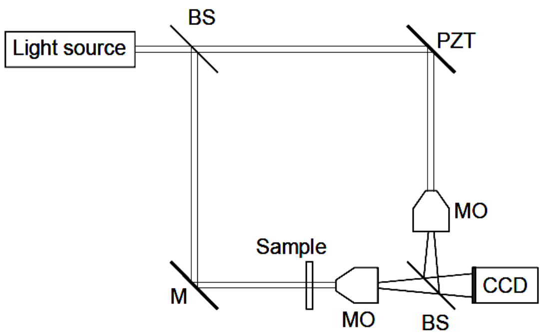

Fig. 1.2. Phase shifting digital holographic microscope

DHM is an ideal solution to perform systematic investigations on large volumes of micro-devices and micro-optical devices. Real time image reconstruction and rendering is henceforth possible, thus providing a new tool in the hands of micro- and nano-system engineers.

Very high accuracy could be obtained by using a MO with a high numerical aperture (NA). The role of this High NA MO is to provide a simple mean to adapt the sampling capacity of the camera to the information content of the hologram.

If longitudinal accuracies can be as low as one nanometer in air or even less in elevated refractive index media, the lateral accuracy and the corresponding resolution is less good, but can be kept at a sub-micron level by the use of a high NA MO. In the present state of the art, it can be kept currently below 600 nm. On the other hand, the accuracy may be also limited by the weak intensities of the optical signals from the nanometer size diffracting objects.

2. Electronic Speckle Pattern Interferometry

Electronic Speckle Pattern Interferometry (ESPI) was born from the desire to replace photographic hologram recording and processing by recording with electronic cameras. ESPI is a method, similar HI, to measure optical path changes caused by deformation of opaque bodies or refractive index variations within transparent media. In ESPI electronic devices (CCD's) are used to record the information. The speckle patterns which are recorded by an ESPI system can be considered as image plane holograms. Image plane holograms are holograms of focussed images. Due to the digital recording and processing, ESPI is designated also as Digital Speckle Pattern Interferometry (DSPI). Another designation is TV-holography. However, instead of hologram reconstruction the speckle pattern are correlated.

The principal set-up of an Electronic Speckle Pattern Interferometer is shown in figure 2.1. The object is imaged onto a CCD by a lens system. Due to the coherent illumination the image is a speckle pattern. The speckle size depends on the wavelength, the image distance and the aperture diameter.

The speckle size should match with the resolution (pixel size) of the electronic target. This can be achieved by closing the aperture of the imaging system.

The speckle pattern of the object surface is superimposed on the target with a spherical reference wave. The source point of the reference wave should be located in the centre of the imaging lens. Due to this in-line configuration the spatial frequencies are resolvable by the CCD. In practice the reference wave is coupled into the set-up by a beam splitter (as shown in figure 2.1) or guided via an optical fibre, which is mounted directly in the aperture of the lens system.

Interference phase measurement with ESPI require application of phase shifting methods. In each state at least three speckle interferograms with mutual phase shifts have to be recorded.

The total number of electronic recordings to determine the interference phase is therefore at least six.

Speckle interferometers are commercially available. These devices can be used nearly as simple as ordinary cameras.

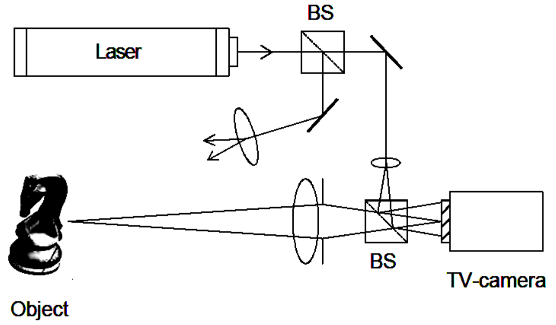

Fig. 2.1. Electronic Speckle Pattern Interferometer

3. Digital Holographic Interferometry

The idea of Digital Holographic Interferometry was to record "real" holograms (not holograms of focussed images) by an electronic device and to transfer the optical reconstruction process into the computer. The method is characterized by following features:

- No wet-chemical or other processing of holograms (as for ESPI).
- From one digital hologram different object planes can be reconstructed by numerical methods (numerical focussing).
- Lensless imaging, i. e. no aberrations by imaging devices.
- Direct phase reconstruction, i. e. phase differences can be calculated directly from holograms, without interferogram generation and processing. This interesting feature is only possible in DHI, conventional HI as well as ESPI need phase shifted interferograms (or another additional information) for phase determination.

The scheme of Digital HI is shown in figure 3.1. The upper left and upper right figures present two digital holograms, recorded in different states.

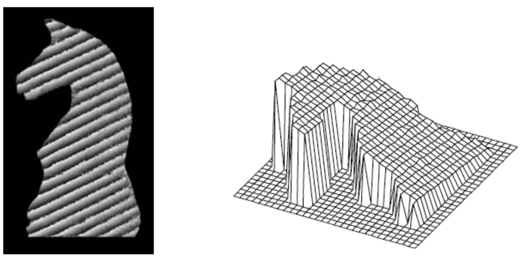

Fig. 3.1. Digital Holographic Interferometry

Between the two recordings the knight has been tilted by a small amount. Each hologram is reconstructed separately by a numerical Fresnel transform. The reconstructed phases are depicted in the two figures of the middle row. The phases vary randomly due to the surface roughness of the object.

DHI and phase shifting ESPI are competing techniques. ESPI is working since many years in real-time, i. e. the recording speed is only limited by the frame rate of the recording device (CCD). In addition the user sees directly an image of the object under investigation, while this image is only available in DHI after running the reconstruction algorithm. This what you see is what you get feature is helpful for adjustment and control purposes. On the other hand the time for running the DHI reconstruction algorithms has been reduced drastically in recent years due to the progress in computer technology. Digital holograms with 1000x1000 pixels can nowadays be reconstructed also nearly in real-time.

Another slight present disadvantage of DHI is that the spatial frequency spectrum has to be adapted carefully to the resolution (pixel size) of the CCD.

Summary

DHM provides an absolute phase image, which can be directly interpreted in term of refractive index and/or profile of the object. Very high accuracies can be achieved, which are comparable to that provided by high quality interferometers, but DHM offers a better flexibility and the capability of adjusting the reference plane with the computer, i.e. without positioning the beam or the object.

By replacing the photochemical procedures with electronic imaging and having a direct numerical access to the complex optical field, a wide range of new imaging capabilities become available, many of them difficult or infeasible in conventional holography. Increasing number of researchers in traditional physics and electrical engineering departments as well as all other areas of engineering, biology, and medicine are interested in exploring the potential capabilities of digital holography.

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Надійшла до редколегії 17.08.2011

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МЕТОДИ ТА ЗАСОБИ ВИМІРЮВАННЯ ЦИФРОВОЇ ГОЛОГРАФІЇ В МІКРО ТА НАНО МЕТРОЛОГІЇ

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Необхідність в мікро і нано метрології очевидна, оскільки критичні розміри поступово зменшуються і геометрична складність об'єктів збільшується. Доступні технології виявляються неістотними. Для того, щоб вирішити завдання такого типу, необхідно об'єднати дослідницькі і конструкторські зусилля. Розробники повинні враховувати нові вимірювальні *принципи і устаткування, правила допуску і процедури для досягнення єдності вимірювань і калібрування. Цифрова голографія – це нова технологія по створенню зображень, яка успадковує багато унікальних здібностей традиційної голографії, проте дає нові рішення до деяких ключових проблем, які обмежуються використанням і надалі розвитком.*

Ключові слова: *нанометрологія, цифрова голографія, мікроскопія, інтерферометрія, CCD-камера.*

МЕТОДЫ И СРЕДСТВА ИЗМЕРЕНИЯ ЦИФРОВОЙ ГОЛОГРАФИИ В МИКРО И НАНО МЕТРОЛОГИИ

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Необходимость в микро и нано метрологии очевидна, так как критические размеры постепенно уменьшаются и геометрическая сложность объектов увеличивается. Доступные технологии оказываются несущественными. Для того, чтобы решить задачи такого типа, необходимо объединить исследовательские и конструкторские усилия. Разработчики должны учитывать новые измерительные принципы и оборудование, правила допуска и процедуры для достижения единства измерений и калибровки. Цифровая голография – это новая технология по созданию изображений, которая наследует много уникальных способностей традиционной голографии, однако дает новые решения к некоторым ключевым проблемам, которые ограничиваются использованием и в дальнейшем развитием.

Ключевые слова: *нанометрология, цифровая голография, микроскопия, интерферометрия, CCD-камера.*