Enlarging the application range of digital holographic microscopes for deformation of rough surfaces

Andreas Brunn*, Yves Delacrétaz**, Christian Depeursinge**, Yves Emery***, Andreas Ettemeyer*

** Interstaatliche Hochschule für Technik Buchs NTB, Institute for Production Metrology, Materials and Optics, CH-9471 Buchs, Switzerland*
***École Polytechnique Fédérale de Lausanne EPFL, STI, Microvision and microdiagnostics group (MVD), CH-1015 Lausanne, Switzerland*
****Lyncée Tec SA, PSE-A, CH-1015 Lausanne, Switzerland*

mailto:andreas.brunn@ntb.ch

A specific adaption of speckle pattern measurement applied on a single wavelength DHM is presented, making 3D deformation measurements possible on objects whose contour cannot be measured due to their surface roughness.

1 Introduction

Digital holographic interferometry (DHM) is a technique to measure the contour of object surfaces or, more precise, to retrieve wavefronts. In the referred setup, coherent light is divided into object beam and reference beam. The object beam is guided through a microscope objective (MO) onto the object surface. Its reflections are then imaged by the objective and a tube lens onto an image plane. The reference beam is slightly inclined towards the optical axis and being overlapped to the object beam. From the resulting hologram, the spatial amplitude and phase distribution of the reflected wavefront can be gained by applying a spatial phaseshift algorithm as described in [1], wherein the reflected wavefront is separated in Fourier space and its modulation removed.

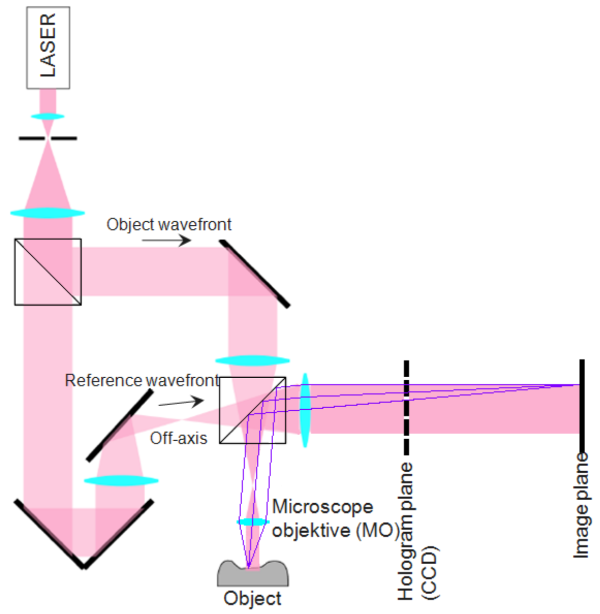

Fig. 1 *Referred digital holographic microscope setup in off-axis configuration*

Although possible, the hologram is usually not recorded at the image plane, as shown in Fig.1, to avoid undersampling of high spatial frequencies. Then, the retrieved wavefront is numerically propagated from the hologram to the image plane in order to read off its amplitude and phase distribution at that position.

2 Problem description

2.1 Numerical aperture limitations

The most evident limitation in practise for measuring rough (in the sense of causing speckled wavefronts) surfaces is the numerical aperture (NA) of the used MO. This is due to the large angular scattering range which exceeds the acceptance angle for increased roughness. The fulfilment of this condition can be observed in the amplitude distribution of the Fourier transformation of the hologram, where virtual and real images are found laterally shifted from the origin due to their spatial modulation by the reference wavefront. In fig. 2 left, a microlens array was measured, the spatial distribution of its amplitude obviously not truncated by the NA, marked by the red circle. In contrary, fig. 2 right shows a measurement of a homogeneous rough surface with broader spatial distribution clearly truncated by the NA, limiting the spatial extension of the captured wavefront and irreversibly loosing information of the wavefront's shape.

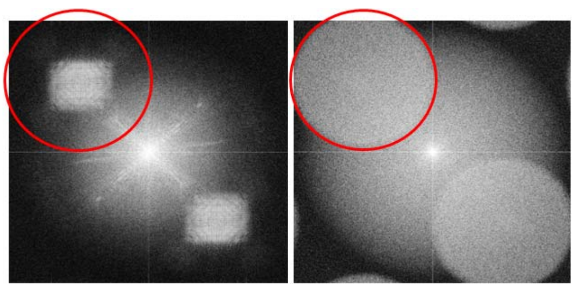

Fig. 2 *Examples of Fourier transformations of holograms*

The amplitude portion spread around the origin of the transformation is called "zero order", containing also unmodulated reflections not originating from the object surface and thus leading to errors in object wavefront reconstruction. As the rough surface has lower reflectivity within the solid angle of the NA, the power ratio between zero order and virtual image is smaller, causing a wider spatial spread and larger influence of mechanical instabilities when maintaining the dynamic range of the CCD array. Due to the spectral spread, the filter must be broadened while the noise distribution is also more widespread and even overlapping.

Both, loss of wavefront information and decreased signal-to-noise ratio (SNR) are inherent problems of the surface itself and handicap measurements.

2.2 Deformation measurement

Despite this hindered situation for absolute measurements, differential measurements are still possible with marginal impact. This is advantageous, when a temporal deformation of an object surface shall be measured rather than its contour. This requires the acquisition of two holograms, between which the deformation took place, and the analysis of their difference, which will be summarised here.

3 Out-of-plane deformation

Analysing the out-of-plane (OOP) deformation is calculating the difference of the two wavefront's phases. The task to overcome the mentioned loss of wavefront information and lowered SNR gets more demanding for increased amounts of deformation.

4 In-plane deformation

4.1 Sensitivity

The phase change of an interferometric setup due to a deformation can be calculated by a cosine projection of the deformation vector onto the normalized sensitivity vector. For usual setups, the highest sensitivity thus exists for surface changes along the optical axis, though the sensitivity orthogonal to the axis, i.e. in-plane (IP) direction, is minimal. For our experimental setup, the interferometric IP sensitivity was found to be small in comparison to the edge length, a pixel of the CCD represents in the object plane. So, an image processing method was implemented for spatially resolved IP deformation measurement.

4.2 Image processing algorithm

As experimental attempt, an image processing algorithm based on crosscorrelation calculation was implemented. Therefore, the amplitude distributions in the image plane of both holograms are calculated. Then, the normalized crosscorrelation of small segments of the second amplitude distribution and segments of the first amplitude distribution of the same size are calculated, whereby the position of the second segment is scanned through the surrounding of the first segment, whose position is fixed. Values near one for the result of the normalized correlation function depict high similarities of the speckle pattern in both segments, so that the lateral movement of a pattern can be determined by the position where the maximum result of the correlation occurs.

As the numerically calculated result of the correlation is in pixelwise shape, the resolution can be enhanced by interpolation. Cubic spline interpolation was found to increase the resolution of the algorithm by factor 20 in practice, still being improvable and thus more than competitive in sensitivity to the interferometric method.

5 Combination to 3D measurement

When merging both deformation measurement procedures with orthogonal sensitivity, the outcome of the IP deformation measurement can be used to analyse the OOP deformation on the same local position, compensating lateral movement between two states as explained in [2].

6 Adapting speckle pattern interferometry to the off-axis DHM setup

In contrary to DHM, most speckle pattern interferometry setups have the sensor positioned in the image plane. This requires a fixed determination of the DHM setup to an in-focus configuration for integration. To avoid that, both methods were applied on the numerical propagated speckle field, maintaining flexibility and the single shot acquisition ability of the DHM in sense of getting OOP and IP information from a single hologram. Of course, two holograms have to be taken in order to measure the deformation between two temporal states. To our knowledge, this is the first proposal to use numerically propagated speckle patterns for IP deformation detection.

Another considerable advantage of applying the IP deformation algorithm on the numerically propagated speckle pattern instead of the conventionally imaged speckle pattern is the zero order filtering property of the Fourier algorithm, prohibiting false positives in correlation calculation.

7 Acknowledgements

We gratefully acknowledge that this work has been funded by the swiss CTI / KTI project number 10651.2 PFNM-NM.

References

[1] Mitsuo Takeda, Hideki Ina, Seji Kobayashi: „Fourier-transform metthod of fringe-pattern analysis for computer–based topography and interferometry“, J. Opt. Soc. Am., Vol. 72, No. 1, January 1982

[2] A. Andersson, A. Runnemalm, M. Sjödahl: „Digital speckle-pattern interferometry: fringe retrieval for large in-plane deformations with digital speckle photography“, Appl. Optics, Vol. 38, No. 25, September 1999