PhD Thesis

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New possibilities of comparative displacement measurement in coherent optical metrology

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Introduction

Coherent optical methods are widely used for the measurement of shape, change of shape or displacement of objects with diffusely scattering surface. Besides conventional methods that use hologram plates, new ones have also appeared based on electronic or digital image recording, applying TV-cameras, CCD camera, or recently CMOS cameras. Because computer processing of image data is incredibly fast and flexible today and data storage systems are capable of storing a huge amount of information on small places, digital techniques have replaced conventional ones in many fields. Both speckle interferometry and holography have digital realization, these are Electronic or Digital Speckle Pattern Interferometry (ESPI or DSPI) or with another name TV-holography, and computer or digital holography.

TV-holography is a widely used method capable of measuring shape, displacement or vibration modes with interferometric sensibility. By simply calculating the difference of the speckled images recorded in the measurement, their correlation (by phase) can be determined. The so obtained correlation fringes contour the measured quantity (shape, depth profile, a component of the displacement field, etc.) on the object surface, similarly to the level contour maps of mountains, so these fringes are also called contour fringes or level-fringes.

Digital holography is almost as old as lasers and conventional holography; it appeared first in the late sixties. Its development was drawn back initially because of the early stage technology or the lack of computers, digital image-recording and -displaying devices. The spreading and the fast development of personal computers and high resolution digital cameras gave a great impulse to this field in the past decade, and the appearance of a new device family, Spatial Light Modulators (SLMs), led to new possibilities of technological improvement. Today, the performance of digital holography made it applicable to measurement tasks as well: shape and displacement can be measured with interferometric sensibility. The primary results of these methods are images showing interference contour fringes related to the measured quantity.

Interferometric measurement methods are suitable to detect hidden material defects, because thanks to their high sensibility they can show the different behavior of the object due to the defect, when a mechanical or another type of load is applied. The faulty and the fault-free object have different mechanical response (change of shape, deformation, displacement) to the same load, but this difference is often so small, that despite the high sensitivity a significant load has to be applied. But in this case, both objects will have a large deformation, which results in too dense, not resolved, unprocessable contour fringes. The maximum allowed fringe number or density is further limited by the strongly limited size of the images (e.g. 1000*1000 pixels) used in digital techniques.

Comparative measurement methods were developed to overcome this problem. Following its usual terminology, two similar objects, a so-called master object considered to be fault-free and a test object under investigation are subjected to the same load under same conditions, and the difference of their deformation due to the load is measured directly in an appropriate manner. This difference practically characterizes the effect of possible material faults, not the load, and is significantly smaller, than the two original deformations, so the contour fringes related to it are not so dense.

There are several comparative measurement methods in the field of speckle interferometry and holography. These are: comparative holographic Moire-interferometry, comparative speckle interferometry, and Difference Holographic Interferometry (DHI) developed at our department. Some of these methods require the presence of both objects in the measurement setup, while others store the states of the master and/or test object on holograms, and the appropriate object states are present only holographically in the measurement. The latter methods have an advantage: the master object has to be subjected to the load only once, and the object states recorded before and after it can be used in the measurement as an etalon, and no material defect will be developed due to serial loads of the master object. Fringe-compensation holographic interferometry and fringe-compensation TV-holography were developed at our department, and are capable of measuring the difference of a real object's displacement and a simulated displacement. Comparative shape measurement can be performed by a spatial light modulator in digital holographic interferometry. This method makes remote/distant measurement possible, in which the master and test object are present not only at different times, but at different places in their own measurement setups. At one of the places (primary location) digital holograms of the master object and its states are recorded, at the other place these holograms are received via some kind of digital channel (e.g. the internet) from the primary location and are used for comparative measurement by inspection of the test object.

Aims of the research

One aim of this work was the further investigation of the fringe compensation method in displacement measurement TV-holography, its application to real comparative and self-compensation measurements, and to investigate the automatization possibilities of self-compensation. It was aimed to verify the limitations of the method.

Another aim of this work was to develop comparative displacement measurement methods in the field of digital holography, which require only simple and known optical setups, are applicable to other type of measurements (e.g. shape), and the comparison or fringe compensation can be performed after the actual optical experiments making remote measurement possible as well. A further aim was to apply, improve and investigate comparative digital holographic interferometry for displacement measurement purposes, and the application of digital holographic illumination in TV-holography for comparative displacement measurement.

Devices used in the research

The experiments were performed in the laboratory of the Optical Metrology Group at the Department of Physics, BUTE. The substantial used devices were: a 35 mW power continuous-wave He-Ne laser, a 1280x1024 pixel resolution CCD camera with 6,7 micron pixel size, a 800x600 pixel resolution liquid-crystal spatial light modulator with 32 micron pixel size, an f=55 mm focus length f/2.8 aperture Micro-Nikkor objective, a piezoelectric phase-shifter, and a mechanical phase-shifter. Computer software used: Corel Photo-Paint 9.xx+, a software calculating fringe-compensation and phase fringes developed at our department, HoloVision 2.2, and a self-developed digital holography software (in MATLAB environment).

New scientific results

1. **Comparative and self-compensating displacement measurement using TV-holography**

The fringe compensation method introduced previously in TV-holography was applied successfully in such cases, where the displacement field to be subtracted is not simulated, but is originated from a real measurement[1]. The ideal way of producing the phase image representing the displacement field to be subtracted, which is one of the inputs of the fringe compensation method, was investigated in two cases. It was shown, that the Gaussian-profile low-pass filtering of the intensity contour fringes referring to the displacement is expedient in the case of comparative measurement of two objects, and if the displacement field is freely re-scalable, then it is advisable to do it with the continuous unwrapped phase map of a smaller displacement. In contrast, in the case of the self-compensation of one object it is better to keep the displacement to be subtracted at its original scale - or else parasite fringes will occur, which may corrupt proper image processing -, and it is better not to filter the speckle noise and not to unwrap the phase contour fringes. The possibility of applying unwrapped phase images left in their $[0,2\pi]$ range to fringe compensation method is an interesting and unexpected result, especially in that case, where no picturesque step-like jumps are observable. This latter case is worth of further investigations, because it can lead to better understanding of how fringe compensation works. The best difference intensity contour fringes were produced using the above mentioned conditions in the two cases, which means fine visibility and image-processing features.

By investigating the simple parallel fringes of rigid-body rotation it was shown, that the visibility of the fringes related to the difference of the two rotations with similar magnitude is basically determined by the larger rotation angle. The visibility versus this rotation angle was investigated with a series of measurements. When a non-uniform displacement function is measured, the fringe visibility is also location dependent and can be estimated from the results obtained with the rigid-body rotation inspection, because such a displacement field can be represented as a set of locally tilted/rotated small surface elements. Finally it was shown, that the automatization of the self-compensation is not possible, because no mathematical algorithm exists which is capable of unwrapping noisy phase-contours with keeping the appropriate profile of the real displacement.

2. **Optimalization possibilities in digital holographic interferometry**

A simple method was proposed for the improvement of the gray-scaling of floating-point image data in the numerical reconstruction of digital holograms, which uses the selection or exclusion of appropriate sections of the whole data matrices. A method called artificial phase-shifting[2] was proposed in the processing of interferometric contour fringes and was compared with direct phase difference calculation. The method makes use of a wider range of image processing algorithms possible, thus the filtering of unwanted speckle noise can be performed more efficiently. The possibilities of enlarging numerically reconstructed images were inspected[3], and it was shown that if enough computing capacity is present, increasing the size of digital holograms without interpolation can be used to increase image plane resolution. The methods mentioned above are independent from each other and can be combined. Together they improve the application of digital holographic interferometry significantly to simple and comparative measurements, as well as to the measurement of other quantities than displacement.

3. Comparative displacement measurement in digital holography using numerical calculation[2]

A new numerical method was proposed for comparative interferometric measurements, which is capable of directly measuring the difference or sum of the displacement of two objects put in the same optical setup, and the principle may be used for comparative shape measurement as well. The method requires a usual optical setup, and the comparison can be performed on the computer after recording the digital holograms. The comparative intensity contour fringes have lower visibility, than the non-comparative ones, as expected. The visibility of the preceding fringes was investigated with a series of fringes with increasing rigid-body rotation, and it was shown that the decrease of the visibility versus rotation angle is due to speckle correlation. The possibilities of using the proposed method for remote measurements are discussed.

4. Fringe compensation displacement and shape measurement in digital holography using simulated waves[3]

A new method applying simulated waves is proposed, which is capable of the direct measurement of the difference or sum of the displacement of a real object and a simulated displacement. The method requires a usual optical setup, its mathematical formulation is related to the method shown in point 3., and it is practically the digital holographic equivalent of fringe compensation in TV-holography. In contrast with the previous method, the comparative fringes have the same visibility as the non-comparative fringes. The method was successfully applied with a known shape measurement technique applying only one wavelength but two illumination directions. Similarly to the previous method this one may also be used with other interferometric measurements, like two-wavelength contouring. For the successful application of the method it is essential to match the simulated wave to the real object wave precisely, and to model the theoretical displacement field or shape of the object under inspection properly.

5. Improving optical reconstruction, comparative displacement measurement using difference digital holography and TV-holography using optically reconstructed digital holograms[4]

A new improved optical setup was made for the optical reconstruction of digital holograms. The telescope-like system used is capable of reconstructing the images of objects stored in digital holograms in a shorter distance with the same size, and the positioning of the image is easier. By converting the digital holograms recorded in real-life experiments the efficiency of the reconstruction is improved, and the hologram-diffraction spots are well separated spatially. The inspection of the properties of digital holographic illumination showed, that the relatively large objective speckles projected onto the object surface mean a disadvantageous inhomogeneous illumination, which will hopefully be overcome by technological development soon. The new reconstruction setup was applied successfully for comparative displacement measurement using difference digital holography and TV-holography, but due to technological limitations the detailed analysis of these methods seemed to be too early. These two-step methods are naturally applicable to remote measurements, where the two objects under inspection are present at different time and location in their own different optical setups. The first step of a comparative measurement is to record digital holograms of one of the objects, and in the second step these holograms are used for digital holographic illumination in one of the mentioned measurement techniques, where the other object is present.

Despite the difficulties it was shown, that in the case of TV-holography the ideal ratio of the intensities in the two arms of the speckle interferometer is not 1 to 1, but 1 to 5 (object beam to reference beam), and this may be explained with the suppression of the grainy speckled illumination with the reference beam. An important discrepancy was also found compared to difference digital holography, namely in a full comparative measurement only one contour fringe system out of the four available displacements' has a better visibility than the others (this one shows the contours of the test object displacement placed in the speckle interferometer), which confirms the explanation of the existing non 1 to 1 ideal intensity ratio.

Publications concerning the thesis

1. B. Gombkötő, J. Kornis, Z. Füzessy, Sz. Beleznai, "Displacement measurement using fringe compensation TV-holography: limitations and properties", Optical Engineering 43(03) (2004), 684-688

2. B. Gombkötõ, J. Kornis, Z. Füzessy, "Difference displacement measurement using digital holography", Opt. Comm. 214 (2002), 115-121

3. B. Gombkötő, J. Kornis, Z. Füzessy, M. Kiss, P. Kovács, "Difference displacement measurement by digital holography using simulated wavefronts", Appl. Opt. 43 (2004) 1621-1624

4. B. Gombkötõ, J. Kornis, Z. Füzessy, T. Rózsa, "Difference displacement measurement using digital holograms as coherent masks", Proc. of SPIE Vol. 5144 (2003) 578-584

5. Gombkötő Balázs, Kornis János, Füzessy Zoltán, "Különbségi elmozdulásmérés digitális holografikus interferometriával", Kvantumelektronika 2003 Szimpózium, Budapest, 2003. okt. 21., BME, P-5, English title: "Difference displacement measurement using digital holographic interferometry"

Other written material related to the thesis

Zs. Papp, J. Kornis, B. Gombkötõ, "New methods in recording and reconstruction of digital holograms", Proc. of SPIE Vol. 5144 (2003) 170-174

Research related to digital holography was mainly performed as part of an international co-operation, where reports were made for our foreign partners twice a year. The title of the research contract is „Possibilities and limitations for the comparative control of the change of shape and shape itself using modern coherent-optical measurement techniques", or shortly "Distant Shape Control" or DISCO.

Z. Füzessy, J. Kornis, B. Gombkötő, "Implementing digital holography", Report II., 2002.01.01-2002.06.30

Z. Füzessy, J. Kornis, B. Gombkötő, "Implementing digital holography for deformation measurement", Report III., 2002.07.01-2002.12.01

Z. Füzessy, J. Kornis, B. Gombkötő, "Experimental demonstration of the quality reduction of the results as function of laser power at comparative measurement applying digital holography", Report IV., 2003.01.01-2003.06.30

Z. Füzessy, J. Kornis, T. Rózsa, B. Gombkötő, "Investigation of the upper measuring limit of digital holographic methods", Report V., 2003.06.01-2003.11.30