NEW METHODS IN COHERENT OPTICAL METROLOGY WITH THE COMPUTER BASED MANIPULATION OF WAVEFRONTS

PhD thesis

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2012

Introduction

The intensity of light waves is the only quantity that can be measured with a digital camera. It means that the phase information, therefore the complex amplitude of waves can not be determined directly. The main idea of Digital Holographic Interferometry (DHI) and Electronic Speckle Pattern Interferometry (ESPI, also named TV-holography) is that the phase information is encoded in an interference pattern. For the recording of images CCD or CMOS digital cameras are used, which corresponds to the sampling and quantization of the interference patterns. It means that the pixel size, sensitivity and signal-to-noise ratio of the applied camera plays an important role. The principle of reconstruction of the data encoded in the digital hologram is also based on wave theory. These coherent optical measuring techniques are widely used methods to measure displacement, deformation and shape of diffusely scattering surfaces with high precision (in the range of the wavelength of light). The main advantages of digital methods are that measurements can be performed in non-contact, non-destructive way combining with the wide range of computer based processing of images.

The common property of DHI and ESPI is that the optical path difference, which is caused by the deformation or shape of objects, can be calculated directly from a contour fringe system, but the derivation of fringes is based on different physical principle. In DHI setups they are interference fringes, but in ESPI the phase correlation between the speckle patterns produces them. In the correlation process we loss the phase information, but it is possible to recover it by recording of phase shifted images.

DHI and ESPI are competing methods, because the image subtraction in ESPI is easier and quicker than the numerical reconstruction process in DHI, but the information content of digital holograms is higher. In practice the quality of fringes is the most important requirement of a successful experiment. An obvious limit of the methods is that the too large displacements or uneven surfaces result dense fringes in a relatively small area. Although the correlation of the object wave fields is large enough to produce fringes with sufficient visibility, the too dense fringes of a larger displacement are practically invisible, because the cameras are discrete devices and sampling theory plays an important role. The minimum fringe spacing in pixels and the noise determine whether or not a deformation can be processed. The maximum allowed fringe number is further limited in DHI, because the image of the object under investigation fills only a section of the whole virtual wave field in the image plane. Mainly from these reasons the major issue is the extension of the upper measuring range, which can be accomplished by applying superimage, comparative or fringe compensation methods. The later is a computational comparative measuring technique, which is based on the artificial phase manipulation of the complex amplitude of reconstructed waves. In the development and investigation of these methods a lot of remarkable scientific results can be associated with the Department of Physics.

The rapid development of electronics increases the number of computer-controlled active optical elements (digital cameras, spatial light modulators, computer controllable mirrors) in measuring setups. It means that automated measuring systems can be built, which can continuously adapt themselves to the change of measuring conditions and environment with the real-time processing of recorded images. These types of setups are called adaptive measuring systems.

The rapid development of high quality spatial light modulators (SLM) is very important in the improvement of optical reconstruction of digital holograms. This active optical element led to new possibilities in the field of comparative measurements. The SLM is also capable to generate computer calculated wave fronts (not belonging to an existing object), and multiple projections can be performed during the measurement time.

DHI and ESPI measurements are performed in interferometers; therefore they are sensitive to vibrations, which could be an important problem in industrial atmosphere. The application of phase retrieval methods in referenceless digital holographic setups is one of the most intensively researched field of coherent optical metrology to get around this drawback. The core of the methods is the recording of multiple intensity patterns of the same beam at different positions along the optical axis. The algorithms mostly based on iterative methods, but deterministic ones also exist. The results can be found in the literature present successful phase retrieval only for millimeter sized objects. The main aims of current research works are the extending of object size can be examined and the implementation of technique for measurements of displacement fields.

Aims of the research

I have joined to the Optical Metrology Group of Department of Physics to perform my research. The main aims of my work were the further development of DHI and ESPI measuring techniques and the design and elaboration of new methods. I have summarized my goals in five sections according to the thesis points.

1. Investigation of fringe compensation in detail. Development of measurement method to pre-estimate the virtual displacement profile used for compensation. Investigation of the extended measuring range. Introduction of qualifying method to compare the upper measuring ranges of different setups.

2. Development of automated evaluation of interferograms in digital holographic interferometry. Implementation of handling of fringe systems with high density and processing of multiple displacements according to their components.

3. Application of optically reconstructed computer generated holograms in coherent optical metrology. Implementation of computer based numerical modeling of optical reconstruction. Development of adaptive measuring system based on holographic object illumination for measurements of displacement fields and shapes of objects.

4. Development of double-exposure phase calculation method in ESPI measurement setup based on holographic object illumination. Measurement of displacement fields of objects with transient behavior. Application of method to solve a specific measurement problem.

5. Investigation of referenceless digital holographic measurements. Implementation of successful phase reconstruction of centimeter-sized objects. Development of a suitable method for measurement of displacement fields.

The actuality of the chosen theme and objectives is that the development of active optical elements and digital processing open new possibilities for further development of current methods or for the development of new ones.

Methods of investigation and devices used in experiments

The measurements of my PhD work have been done in the laboratories of the Optical Metrology Group at Department of Physics of BUTE. The substantial used devices were:
I used a 500mW power continuous-wave Kr-ion gas laser (λ=647.1nm) and a 50mW power continuous-wave He-Ne laser (λ=632.8nm) as coherent light sources. The images were captured with 1600x1200 and 1280x1024 pixel resolution CCD cameras, which have pixel size of 4.4µm and 6.7µm. The optical reconstructions of digital holograms were performed using a liquid-crystal spatial light modulator (LC SLM) with the resolution of 800x600 and 32µm pixel size. To image the scattered waves I used fix and zoom objectives with different focal lengths. The phase shift of waves was implemented using a computer controlled piezoelectric mounted mirror (PZT-mirror). These elements were used at building the measurement arrangements serving my goals.

The most of computer work was done by self developed programs, implemented in MATLAB programming language during my PhD work. They were capable to process and simulate DHI and ESPI measurements, calculate fringe compensation, evaluate the interferograms automatically and control the active optical elements. As starting point for simulations and processing of interferograms I used the previously developed Delphi programs of my supervisor, János Kornis, and the documentation of HoloVision2.2 freeware software.

New scientific results

The new scientific results of my PhD work can be summarized in the following thesis points:

1. thesis [P1, P2, P6]

I have proposed a new method based on fringe compensation, combining two out-of-plane displacement measurements with different sensitivities to extend the practical measurement range of DHI. I have proved that the calculation of displacement field with a less sensitive measurement, then its application for the compensation of a more sensitive one combines the advantages of methods and provides a resolution to maximal deformation ratio that would not be achievable by a single measurement. I have designed and optimized the measurement process in detail. Based on this knowledge I have chosen the appropriate methods with different sensitivities (DHI and desensitized ESPI). I have examined and compared the factors determining the extensibility of measurements limits. I have introduced a qualifying method for the investigation of upper measuring range. It allows the comparison of measuring range of measurements performed with different settings. I have proved that this setup allows evaluating out-of-plane displacements even if the maximum fringe density on the difference digital holographic images is about 1.5–2.2 times bigger than the maximum fringe density calculated from the Nyquist sampling criterion.

2. thesis [P7, P8]

I have realized that fringe compensation is a suitable method for automated evaluation of displacement fields with multiple deformation components, even if the density of fringes on the holographic image is high. I have developed the theoretical background of the separation and recognition of fringe structures belong to various types (deformation, rigid-body rotation) of displacement components. I have showed that the components can be treated independently during the processing of interferograms. I have implemented the process of recognition and compensation (software was developed in Matlab programming language) and optimized it with test runs. I have proved that the automated evaluation of displacement fields is possible using fringe compensation even if the fringes are indistinguishable due to their high density, because the application of random compensations steps in the initial state can make the algorithm convergent.

3. thesis [P3, P9, P10]

I have realized that using computer generated holograms and their fringe compensations as input signals for SLM, the illumination can adapt itself to the change of measuring conditions with the real-time processing of images and feedback. This is the main property of adaptive measuring systems. The automated processing of measurements based on the combination of this approach with the theory of comparative measurements. I have implemented the common computer control of active optical elements, developed the numerical simulation of comparative measurements and optimized the SLM for the optical reconstruction of digital holograms in high quality. The main advantage of method is that it occurs less significant correlation decreasing compared to fringe compensation, which results higher quality interferograms in spite of holographic illumination. The method also allows automated processing of ESPI measurements, which is a further advantage. I have proved that the application of method makes the processing of displacement and one-wavelength shape measurements easier and extend their measuring range.

4. thesis [P4]

I have developed a new ESPI measurement method to calculate phasemaps of slow varying displacements and deformations. I have realized that the phase difference calculation is possible from only two intensity images recorded one before and one after the deformation. It required holographic object illumination and adequate computer generated, phase manipulated digital holograms as input signals for SLM. I have examined the requirements, possibilities and limits of the method. Simulations and experimental measurements testify that the method applicable for phase difference calculation in good quality between two arbitrary states of a transient displacement. I have applied this technique successfully for structural observation of thermally excited archeological materials to detect the inborn cracks in noncontact, nondestructive way.

5. thesis [P5]

I have investigated and developed measuring setups in referenceless digital holography. I have optimized the operation of iterative phase retrieval algorithms with the finding of proper conditions. Compared to the literature of this scientific field I have extended the object size can be examined from millimeter to centimeter range and implemented the technique for the measurements of displacement fields. I have showed that the visibility of contour fringes is the highest in near-field setup. In case of imaging setups I have realized that the iterative phase reconstruction algorithms must be corrected according to the influence of imaging lens system and its finite aperture size to the wavefronts. The results of simulations and experimental measurements testify that the reconstructed phase information is physically correct.

Utilization of results

My research work can be considered as basic research. Based on my results I think two methods can become promising tools for industrial applications. One of them is the adaptive measuring system based on holographic object illumination (3. thesis) and the other is the double-exposure phase calculation method (4. thesis) developed for the measurements of slow varying displacement fields. The latter also uses proper holographic object illumination. I have already presented a specific application field of each method (shape measurement of a part of an engine, structural observation of an archeological sample) in my dissertation. Later I would like to patent the theoretical background of the two methods and my ideas and put them from laboratory into industrial atmosphere after further development. I think industry need shape measurements, adaptive shape measurements at present and the rapid structural monitoring of materials in interferometric setups can be considered also as a promising method.

Publications related to thesis

Scientific papers

P1. Richárd Séfel, János Kornis: "Extension of the upper measuring limit in out-of plane deformation measurement by combination of digital holography and desensitized electronic speckle pattern interferometry" *Optical Engineering*, Vol. 49. Issue 6, pp. 065801-065801-7 (2010).

P2. Richárd Séfel, János Kornis: "Examination of the Upper Measurement Limit in Displacement Measurement Using Fringe Compensation in Digital Holography" *Optics Communications*, Vol. 284. Issue 7, pp. 1792-1797 (2011)

P3. Richárd Séfel, János Kornis, Balázs Gombkötő: "Comparative Electronic Speckle Pattern Interferometry Using Adaptive Holographic Illumination" *Optical Engineering*, Vol. 50. Issue 1, pp. 015601-015601-5 (2011).

P4. Richárd Séfel, János Kornis: "Double-exposure phase calculation method in electronic speckle pattern interferometry based on holographic object illumination" *Applied Optics*, Vol. 50. Issue 23, pp. 4642-4647 (2011)

P5. Balázs Gombkötő, Richárd Séfel, János Kornis: "Full Field Deformation Measurement of Centimeter Sized Objects Using Optical Phase Retrieval" *Optics Communications*, Vol. 284. Issue 12, pp. 2633-2637 (2011)

Conference proceedings

P6. Richárd Séfel, János Kornis: "Deformation and shape measurement by compensation in digital holography" *Proc of SPIE*, Vol. 7358, pp. 735810-735810-10, 2009 (SPIE Europe Optics+Optoelectronics conference, Prague, Czech Republic)

P7. János Kornis, Richárd Séfel: "Automated compensation of fringe pattern in digital holography and TV holography" *Proc of SPIE*, Vol. 7389, pp. 738908-738908-12, 2009 (SPIE Optical Metrology conference, Munich, Germany)

P8. János Kornis, Richárd Séfel: "Identification of deformation components in TV holography and digital holography" *Fringe 09: 6th International Workshop on Advanced Optical Metrology*, 2009 (Stuttgart, Germany)

P9. János Kornis, Richárd Séfel: "Application of holographic optical elements in active interferometers for nondestructive testing" *Proc of SPIE*, Vol. 7619, pp. 76190E-76190E-9, 2010 (SPIE Photonics West conference, San Francisco, USA)

P10. Richárd Séfel, János Kornis, Szilvia Varga-Fogarasi: "Adaptive holographic illumination in comparative electronic speckle pattern interferometry". *Proc of SPIE*, Vol. 8082, pp. 80822K-80822K-9, 2011 (SPIE Optical Metrology conference, Munich, Germany)

Other publications

P11. Séfel Richárd, Kornis János: "Digitális holográfia felső méréshatárának kiterjesztése Drizzle módszer alkalmazásával" Quantumelectronics, P-7, 2008 (Budapest, Hungary)