Coherent Metrology

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The trend towards miniaturization of microelectromechanical systems (MEMS) and micro-opto-electro-mechanical systems (MOEMS) continues to lead to more and more compact devices. Advantages lie in the integration with control electronics, lower power dissipation, higher sensitivity and better performance. Applications cover a wide range of fields, from optical telecommunications to medicine. Part of the functionality and reliability of the devices is based on the displacement and deformation of micromechanical parts under mechanical, thermal, magnetic or electrostatic loads. The measurement of the deformation of such systems is thus of great importance for confirming analytical and finite element models, accessing material and device properties, detecting potential defects and determining performance. Since typical structures exhibit dimensions in the order of some micrometers, it is necessary to measure their deformation with accuracies down to the lower nanometer range. Standardized approaches and calibrated setups are therefore essential for the measurement of displacement and deformation fields in the static and dynamic cases. Our work aims is to develop standards and guidelines for the use of different full-field optical techniques in the measurement of out-of-plane and in-plane displacements of microsystems. This process involves:

- Development of micromechanical reference components designed to deform in a reproducible and precise way when submitted to known loads;
- Calibration of the reference devices by means of optical techniques, performed in laboratory-controlled conditions;
- Determination of the measurement uncertainties according to the guide of expression of uncertainty in measurement (GUM) and certification of the calibration setups allowing for traceability of the observed quantities to the international SI standards.
- After development and calibration, the reference devices may then be used for the general calibration of optical measurement systems used in the MEMS industry.

In the annual report 2007/2008 we reported how the calibration procedure was applied to the in-plane displacements of a micromechanical reference, here in Fig. 1 we show some results obtained with the out of plane MEMS. The application of a voltage produces displacements of different magnitude of central elements of the device. The displacement was measured by using a method based on digital holography. We found a very good agreement between expected and measured displacement. It was shown that the out-of-plane displacements may be performed with an accuracy of 1.0 nm.

Fig. 1: Photo (a) and out-of-plane deformations of the MEMS obtained by applying 15 V (b), 30V (c) and 50 V (d).

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Nanoscale imaging: Deep ultraviolet digital holographic microscopy

A. Faridian, D. Hopp, G. Pedrini and W. Osten

A deep ultraviolet off-axis digital holographic microscope (DHM) has been developed. The microscope has been arranged with as least as possible optical elements in the imaging path to avoid aberration due to the non-perfect optical elements. We employed an ArF Excimer Laser, ExiStar 200 (TUI), lasing at deep UV (193 nm). The laser is pulsed and the setup does not need to operate in vacuum, which make it a robust and practical arrangement for industrial applications. Moreover, a digital camera is commercially available for this wavelength with high UV sensitivity, (PCO Sensicam). A custom-designed objective was constructed to meet the demands of the off-axis setup while having a low price for imaging with a deep UV light source. The objective has a numerical aperture of 0.75 and it can image a field with the radius of 10 µm.

To increase the resolution, oblique illumination was performed through an incident angle of ~10° relative to the normal axis of the object plane. To avoid artifacts appearing in the image, we have performed oblique illumination from four symmetric directions. To test the resolution of the setup we have used our designed template, which includes structures, ranging from 500 to 100 nm in width (Fig. 1.a). Figures 1.b-c show a typical recorded hologram and its Fourier transform. The reconstructed amplitude and phase for two selected oblique directions are shown in Fig. 1.d-g. The amplitude image has been separately reconstructed for each of four directions. We have combined the reconstructed amplitude images, obtained from each individual direction, by adding the complex amplitude of the raw images and without implementing any further image processing technique (Fig. 1.h). In this image the “ito” logo is clear and even the line structures with the width of 250 nm are well-resolved (Fig. 2), that confirms a significant enhancement in resolution compared to the result obtained with a conventional optical microscope (Fig. 2.b.), in which the line structures with the size of 500 nm are the smallest resolvable structures.

![Fig. 1: (a) The Scanning Electron Microscope (SEM) image of the nano-structured template, (b) a typical recorded digital hologram and (c) its Fourier transform, (d-f) the reconstructed amplitude and (e-g) phase of the object illuminated with oblique illumination along “y” and “x” axes, (h) the final image obtained by combining the reconstructed amplitude images taken from four symmetric oblique directions. The scale bar is 3 µm.](image)

![Fig. 2: A fine comparison of (a) the image obtained using our DHM setup, (b) the image taken using a conventional optical microscope with NA:0.7 and (c) the SEM image of the template. (d-f) the magnified section and the inversed intensity profile of the smallest resolvable structure (250 nm).](image)

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Knowledge Management in Virtual Labs and Remote Experiments

M. Wilke, M. Riedel, G. Situ, I. Alekseenko, G. Pedrini, W. Osten

The MWK-funded project BW-eLabs focuses on the development of a collaboration infrastructure for scientists, providing access to remote laboratories, data bases for results (stored as raw data with added meta data) and publication of experimental results. The ITO contributes a remote experiment for holographic microscopic metrology. The experimental setup is shown in Fig. 1.

![Fig. 1: Holographic Microscope](image)

A Nd-YAG Laser is coupled into a fiber, which guides the beam into a coupler that subsequently divides the input laser beam into a reference arm and object arm. The object arm fiber can be switched for different illumination modes, i.e., transmission mode or reflection mode, depending on the property of the object to be investigated. The object is imaged through a 20x/0.5 microscopic objective. The reference fiber is coupled into the system using a beam splitter as shown in Fig. 1, to interfere the reference beam with the object wave. The microscopic table is mounted on an electric-driven 3D positioner, allowing the user to shift the field of view at submicron precision. The object is imaged using a 20x/0.5 microscopic objective and a CCD camera is used to record the hologram. The camera has a large sensing area, and a high numerical aperture can be obtained when it is placed close to the object, even in a lenseless configuration. The hologram is transferred to the computer for subsequent processing, including numeric reconstruction of phase and intensity and the calculation of phase difference compared to previous holograms. The data and control flow of the remote experiment are shown in Fig. 2. Figure 3 shows the frontpanel of the LabView vi used for the control of the experiment. The control is provided by remote desktop system (VNC), connecting through a proxy using an encrypted channel (SSH tunnel), adding standard authentication through the modular authentication system PAM and encryption for security, based on existing software such as Java-Portlets running on the BW-eLabs Portal server and Python modules on the proxy server. The connection to the data base and publication backend eSciDoc is work in progress and will allow automatic storage and access to experimental results, including identification through a unique, persistent digital identifier (DOI). eSciDoc is connected to the OPUS document server at the University of Stuttgart for publication. Sets of actual experimental data can be accessed and referenced through OPUS, using the DOI identifiers. In addition to the generic access using VNC, a 3D virtual environment (Wonderland) is being implemented. This frontend is intended to provide intuitive access to the hardware, as well as support collaboration between users by providing communication channels.

![Fig. 2: Data and Control Flow in BW-eLabs](image)

![Fig. 3: Sample view of the remote panel](image)

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Full-Field Advanced Non-Destructive Technique for Online Thermo-Mechanical Measurement on Aeronautical Structures

I. Alexeenko, G. Pedrini, W. Osten

Thermography is a method used to measure temperature inhomogeneity’s and allows determining defects located at different depths inside composite structures.

Electronic Speckle Pattern Interferometry (ESPI) allows measuring the mechanical displacements of the surface of a structure submitted to loading and to get informations about the elastic parameter and defects of the structure.

A set-up which combines thermography and ESPI was built. The spectral range of the ESPI system was expanded up to the long wave infrared (LWIR) in order to decrease 20 times the sensitivity compared with methods using visible light and allowing the recording of large deformations as they usually occur in aeronautical structures.

Figure 1 shows the sketch of the set-up using a CO₂ laser light source with wavelength 9.3 µm and coherence length 1–1.5 m. The thermographic images and the interferograms are recorded on the same detector which is an uncooled microbolometer infrared camera (VarioCam-hr manufactured by InfraTec). This Focal Plane Array (FPA) detector has 640 x 480 pixels (physical dimension of each pixel is 25 x 25 µm²), its dynamical range is 16 bits and the frame rate is 50 Hz. The imaging system is composed by a Germanium objective with 50 mm focal length. The basic parts of the interferometer have been isolated inside a beam delivery system in order to avoid that unwanted reflections from the surrounding environment hit the detector which is very sensitive and could be destroyed irreversibly by the CO₂ laser radiation. The reference beam was delivered by using a flexible hollow silica fiber with core diameter 300 µm. Attenuators were used to reduce the output intensity for the illumination and reference beams. The system was full automated by using LabView software and NI data acquisition boards (DAQ).

Figure 2 shows a result obtained by using the developed system. The investigated object (part of an aircraft) was a Kevlar 360 x 300 cm² plate with delamination defects located at different depths. The loading system was an infrared lamp located in front of the object that increases the temperature of the sample and produces its deformation. Since we recorded simultaneously holograms and thermal images on the same detector, the separation of these two signals is needed and is done by using a four step algorithm allowing to calculate the phase changes of the coherent wavefront due to the object’s displacement and extract the temperature distribution on the sample surface. From Fig. 2 we may see that thermography and LWIR-ESPI are both able to detect defects located inside the Kevlar plate, furthermore the ESPI system allows to monitor the deformation of the object surface.

Fig. 1: Experimental set-up which combines simultaneous acquisition of holographic and thermal images.

Fig. 2: Phase difference representation of the deformed object: a), and its temperature distribution: b).

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Imaging through tissue using short-coherence digital holography

G. Situ, Y. Zhang, G. Pedrini, W. Osten

Image formation through scattering media using visible light is a subject of great interest. One of the practical aspects of the challenging problem concerns the possible application in identifying internal structures of objects embedded within or hidden behind scattering media like translucent biological tissue, which has great potential in assisting the non-invasive diagnosis of a number of clinical problems such as early detection of tumours. Photons migrating through strong scattering media dominantly undergo multiple scattering, thereby preventing the tissue from being transparent.

We propose an imaging method based on short-coherence lensless digital holography (see Fig. 1). By using a beam splitter, the laser beam is divided into two, one of which is used to illuminate the object behind a scattering medium, and the other as a reference. The two beams are then recombined at the CCD plane. Note that in short-coherence holography interference occurs only when the object and reference photons are from the same coherence volume. Photons take random walks in strong scattering media. The less-scattered photons leave the media first while the multiple-scattered ones are behind. Careful adjustment of the pathlength difference between the two arms enables us to select the early-arriving photons, and reject the diffusive. The recording time is much longer than the coherence time and the diffusive photons are still recorded by the camera and produce a strong noisy background. To reduce the noise and obtain clearer imaging we inserted a ground glass in front of the object to produce speckle illumination. The beam then passes through the object, and the scattering medium. During the recording, we shifted the ground glass stepwise in a transversal direction by using a translation stage, and recorded a hologram at each step. Illumination in this way not only allows the reduction of speckle noise, but also plays a central role in the reduction of the multiple-scattering noise.

We carried out prove-of-principle experiments to demonstrate our technique. The light source was a 3 mW diode laser with the central wavelength 634 nm and coherence length of 40 µm. The object beam sequentially passed through a ground glass, an object printed on a transparent slide [Fig. 2(a)] and a fresh chicken breast slide of 3:1 ± 0:1 mm thickness. The chicken tissue slide was cut in fresh and laid on a microscope slide. The tissue presents very strong scattering as the direct reconstruction is barely recognizable [Fig. 2(b)]. However, by using the proposed method, significant improvement can be observed by averaging 60 holograms as evidenced in Fig. 2(c). The signal-to-noise ratio (SNR) is improved from 1.9 to 4.7. The reconstruction is far better if the tissue thickness is reduced to 2:2 ± 0:1 mm [Fig. 2(d)].

Fig. 1: Experimental setup of the proposed digital Fourier holography for imaging in tissue. LD: Laser diode, BS: beam splitter, LTS: linear translation stage, M: mirror, MO: microscope objective.

Fig. 2: Experimental results. (a) the original image printed on the transparent slide. (b) Reconstruction from one hologram. (c) Image formed by averaging 60 holograms. (d) Same as (c) except that the thickness of the chicken breast is reduced from 3:1±0:1 mm to 2:2±0:1 mm and that z = 21 cm.

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Resolution enhancement in digital holography

C. Yuan, G. Pedrini and W. Osten

Digital holography is a useful tool for three dimensional imaging, vibration and deformation measurement and particle analysis. The resolution of digital holography is determined by the numerical aperture (NA) of the recording system. To increase the NA, we proposed a method where several holograms are recorded in one CCD frame by using spatial multiplexing techniques and structured illumination.

The recording system is depicted in fig. 1. In the object beam arm, an imaging system composed by lens L1 and L2 is used to project a demagnified image of a grating onto the object. The object illuminated by the structured light is magnified by a microscope objective and imaged in front of the recording plane. In the reference beam arm, a lens L3 is inserted to compensate the curvature introduced by the objective in the object beam. A He-Ne laser (λ=633 nm) is used as a light source and a CCD (2452×2054 pixels) records the interference pattern (hologram) produced by the interference between the reference and the object beam. The spatial frequencies of the sinusoid grating are 25.2 lp/mm and 21.0 lp/mm along the x and y directions, respectively. A 3.2× microscope objective with NA=0.12 is used to image the object. A USAF1951 test target has been used to demonstrate the resolution improvement by this system.

Five light beams diffracted from the two dimensional grating illuminate the object from different directions. The zero order diffraction beam carries the low frequency information of the object to the CCD and the other beams shift the high spatial frequencies and allow them to enter into the imaging pupil. Introducing additional spatial frequencies to the imaging system is equivalent to increase the NA and thus enhance the resolution. The low and high frequency components are recorded in one frame and separated in the frequency domain. The resolution is improved by adding the reconstructed five complex amplitudes covering low and high frequency bandwidths. From the experimental results given in Fig. 2 we may see that under on-axis illumination we may resolve the 6th element of the 6th group and by using structured illumination the 6th element of the 7th group is resolved. Therefore, the resolution of the system has been improved from 114.0 Lp/mm (under on-axis illumination) to 228.0 Lp/mm (under structured illumination) in both vertical and horizontal directions.

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Phase retrieval by pin-hole scanning

G. Pedrini, F. Zhang, W. Osten

Holography allows to get the complex amplitude of a wave front by overlapping to it a reference wave. Nowadays, thanks to CCD and CMOS sensors and to modern computer resources, digital holography permits a straightforward and almost instantaneous evaluation of the amplitude and phase. Configuring a separate reference from a single light source, however, entails additional problems and for sources having reduced spatial coherence a filtering is necessary to get a homogeneous beam (e.g. spherical). Furthermore, when the source has low temporal coherence a tedious and sometimes cumbersome process of optimizing the path length between object and reference beams is necessary. Investigations have been made with the purpose to reconstruct amplitude and phase without using a reference beam and thus avoiding the disadvantages described above. We propose a simple non-iterative (deterministic) method to retrieve the phase by using the set-up shown in Figure 1.a). A transmitting or reflecting object is illuminated by coherent or partially coherent light. If we insert an opaque screen in the $x$-$y$ plane with two pin-holes at $A$ and $B$ then two spherical waves are produced and their interference is described by a system of hyperbolic Young fringes which can be detected in a plane located at the distance $z_B$ from the screen. By performing a Fourier transform (FT), (see Figure 1.b), applying a filter in order to keep only one lobe (see Fig. 1.c) and then performing an inverse Fourier transform (iFT) we may get a complex distribution (see Fig. 1.d) and from this be taking into account the geometry of the arrangement we are able calculate the phase difference of the wavefront between the points $A$ and $B$. The phase differences between the points $A$ and $B_j$ may be determined by keeping fix the pin-hole located at $A$ (this will be our reference) and shifting the other one along a grid to different positions $B_j$. In this way we get the complex amplitude at each grid point (see Fig. 1.e) and by using the law of propagation we are able to reconstruct the object wave front at a given distance from that plane. The recording of the interference pattern at $\xi - \eta$ is done by a pixelated detector. The proposed method was at first tested by using simulated pattern (binary ITO logo shown upper left in Fig. 1.a) with random phase added). We simulated...
the recording of interferograms obtained by interfering the spherical wave coming from the reference pin-hole (located at point A) and the waves coming from the other pin-hole which is shifted along a 512x512 grid. From the interferograms, we get the phases, and amplitudes allowing the reconstruction of the object (see Fig. 1.f).

An experiment has been carried out where a 2.5x2.5 mm² transmission mask (see Fig. 2.a) was illuminated by light produced by a Nd:YAG laser. One pinhole was mounted on a computer controlled 2D translation stage and was translated along a 128x128 grid. The interference pattern were recorded by a CCD camera. The retrieved phase at the plane x-y is shown in Fig. 2.b) and the object reconstruction in Fig. 2.c). The quality of the reconstruction is not very good due to the small number of scanned points (128x128).

**Fig. 2:** (a) Original mask used for the experiment (2.5x2.5 mm²). (b) Retrieved phase of the wave front at the scanning pin-hole plane (128x128 points) (c) Reconstructions of the object from the complex amplitude.

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